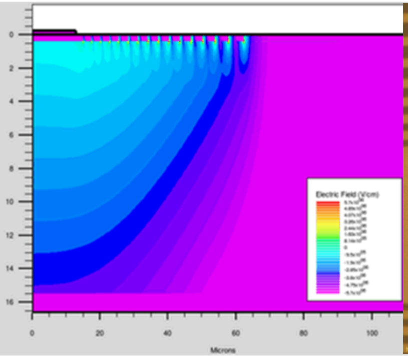
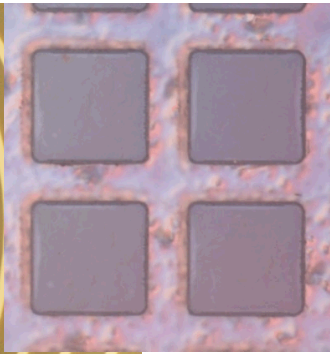
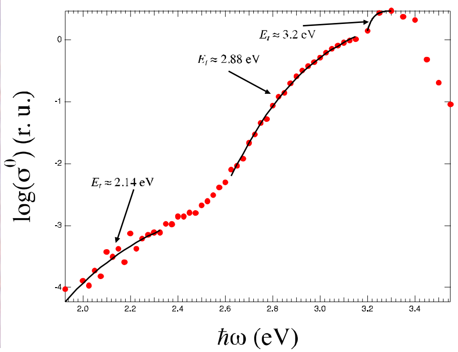
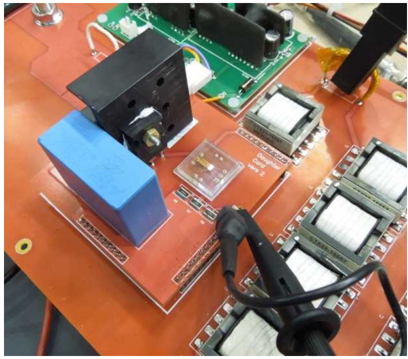
Wide- and Ultra-Wide-Bandgap III-N Semiconductors for Power Electronics

SAND2015-6618PE





Presented by:

Bob Kaplar

Principal Member of the Technical Staff

Sandia National Laboratories

Presented to:

The Ohio State University

Department of Electrical Engineering

June 26, 2015

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Acknowledgements

I'd like to acknowledge Sandia's entire Ultra-Wide-Bandgap Grand Challenge team (~50 people). Unfortunately not everyone can be listed here; key contributors include:

- Epitaxy thrust: Andy Allerman
- Defect physics thrust: Andy Armstrong
- Vertical devices thrust: Jon Wierer
- Lateral devices thrust: Albert Baca
- Device test thrust: Jason Neely
- Management: Jerry Simmons, Rick Schneider, Olga Spahn, Carol Adkins, Vipin Gupta

I'd also like to thank Prof. Siddharth Rajan for inviting me to give the talk

Outline

- **Introduction and motivation**
  - Introduction to Sandia
  - Motivation for WBG/UWBGs in power electronics
- **Vertical devices**
  - GaN PiN diode design and fabrication
  - Doping and defect physics in GaN drift regions
  - $Al_{0.3}Ga_{0.7}N$ PiN diodes
- **Lateral devices**
  - Al-Rich $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ heterostructures

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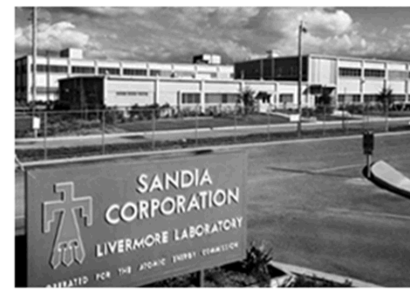
ULTRAWIDE BANDGAP POWER ELECTRONICS

Sandia National Laboratories

Sandia's History

AMERICAN TELEPHONE & TELEGRAPH CO.
BELL SYSTEM
AND ASSOCIATED COMPANIES



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract [illegible] at Albuquerque, New Mexico.

This operation, which is a vital [illegible] atomic [illegible] national defense, and should have the best [illegible] technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an **exceptional service in the national interest.**

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

exceptional service in the national interest.

Sandia's Sites

Albuquerque, New Mexico

Livermore, California

Tonopah, Nevada

Waste Isolation Pilot Plant, Carlsbad, New Mexico

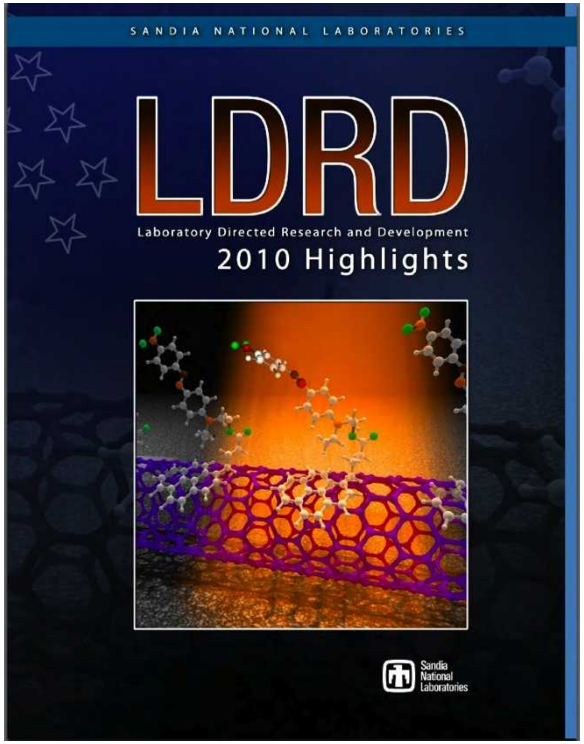
Pantex, Texas

Kauai, Hawaii

Sandia's LDRD Program

➢ ***LDRD: Laboratory Directed Research and Development***

- **Sandia's sole source of discretionary R&D funds**
- **Purpose is "to create…the development of a technical expertise within programs deemed by Sandia Management as important to the future of the Laboratories, DOE, and the nation"**
- **"Grand Challenge" is a special class of LDRD; typically two new starts per year, ~15 full-time equivalent staff**



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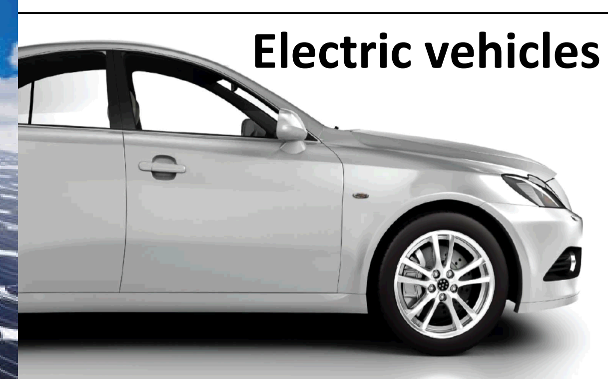
Power Electronics are Ubiquitous



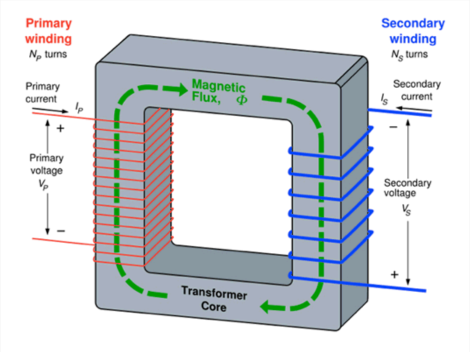
What Are Power Electronics?

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

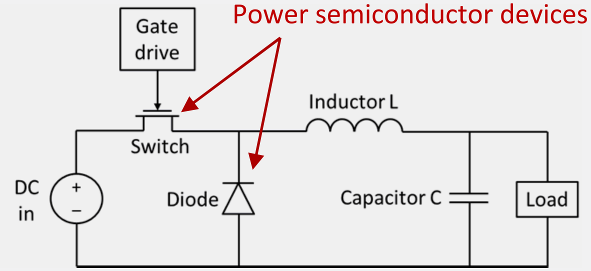
- Current power electronics are limited by the properties of silicon semiconductor devices
- New system capabilities are enabled by:
  - Higher switching frequency (enables better SWaP)
  - Lower power loss
  - Higher temperature operation

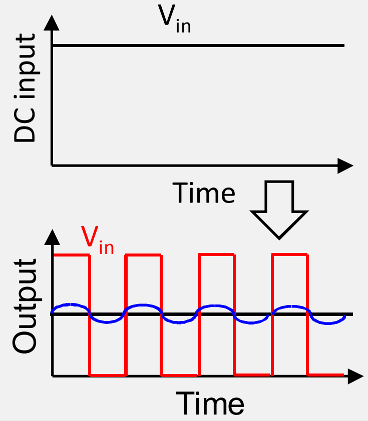
➢ ***Motivation for WBG/UWBG semiconductors***

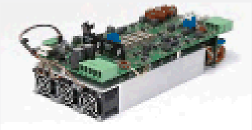
Passive transformers (dumb)



Power Electronics – Active switching (smart)



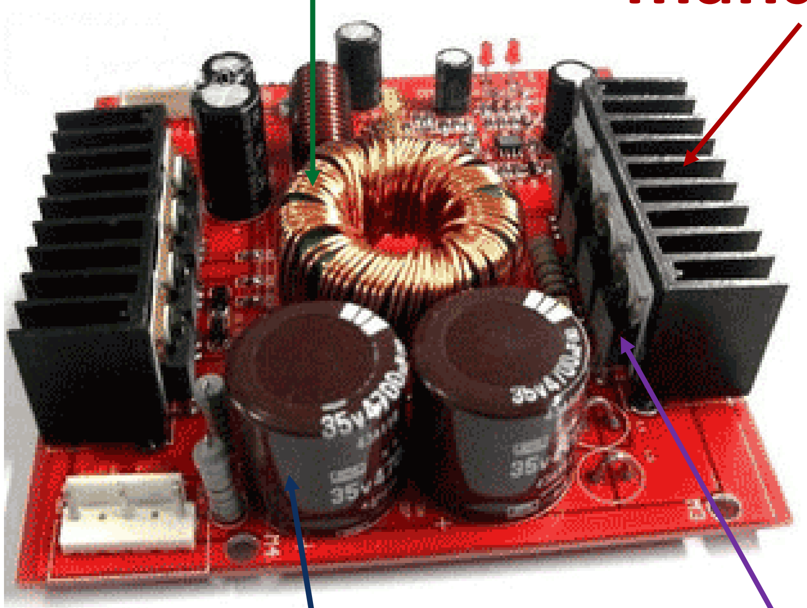




Semiconductor Devices Dictate System Volume and Weight

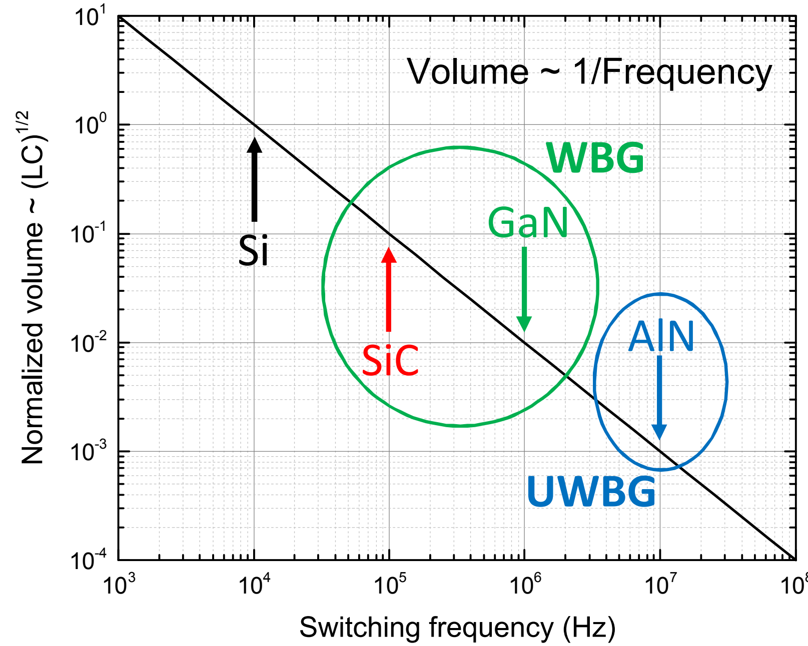
Passive elements and thermal management comprise the bulk of the volume and mass of a power converter

WBG/UWBG materials enable higher switching frequency and better thermal management



Dramatic Reduction in Power Converter Volume with Increasing Bandgap

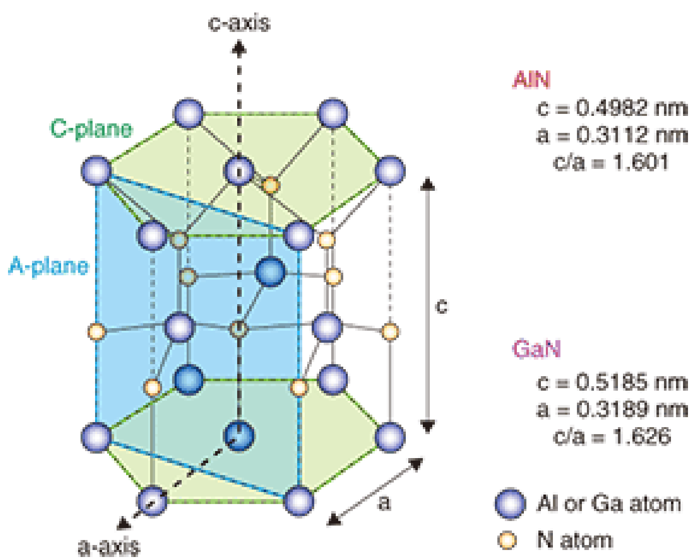
SiC is 10% the volume and weight of Si for equivalent capability (10 kV, 100 A)



New materials and device architectures are needed to continue the trend towards higher performance PE

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	3.3	15.9
Saturated electron velocity (10^7 cm/s)	1	1	2	2.5	2
Thermal conductivity (W/cm·K)	1.5	0.5	4.5	4	3.4



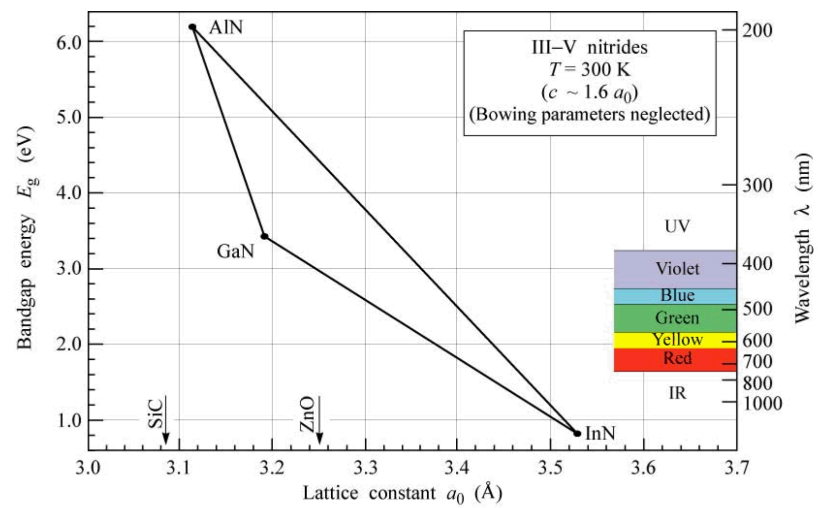
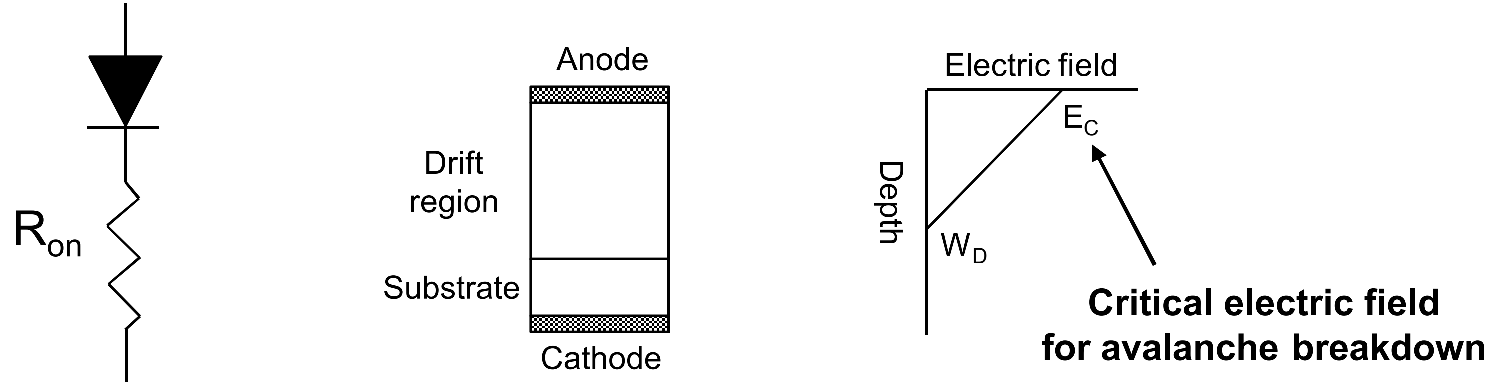


Fig. 12.12. Bandgap energy versus lattice constant of III–V nitride semiconductors at room temperature.

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

Breakdown Voltage and Figure-of-Merit Are Strong Functions of Critical Electric Field



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

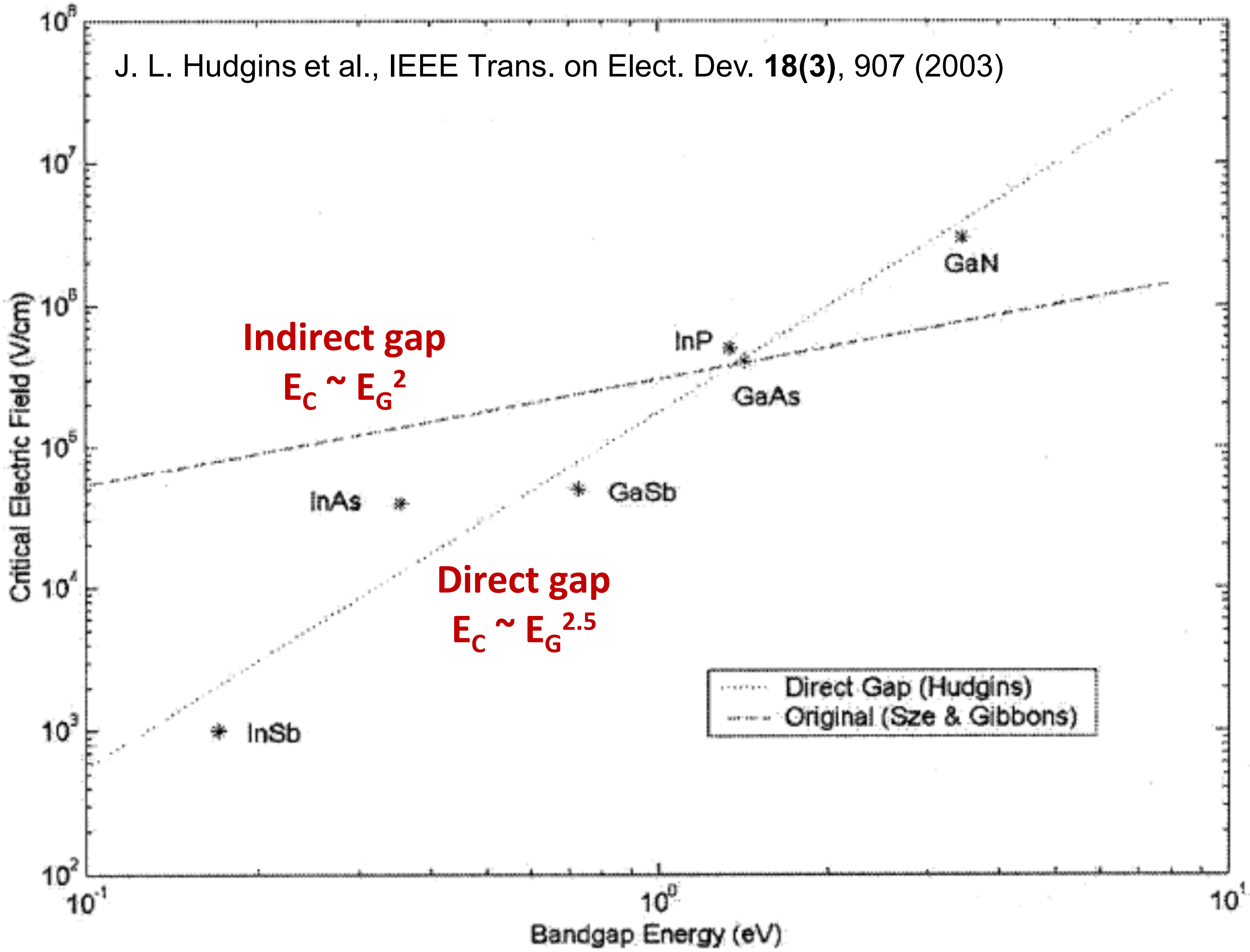
- Combining (1) and (2) gives dependence of V_B on N_D and E_C: $\mathbf{V_B = \varepsilon E_C^2/2qN_D}$

- 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

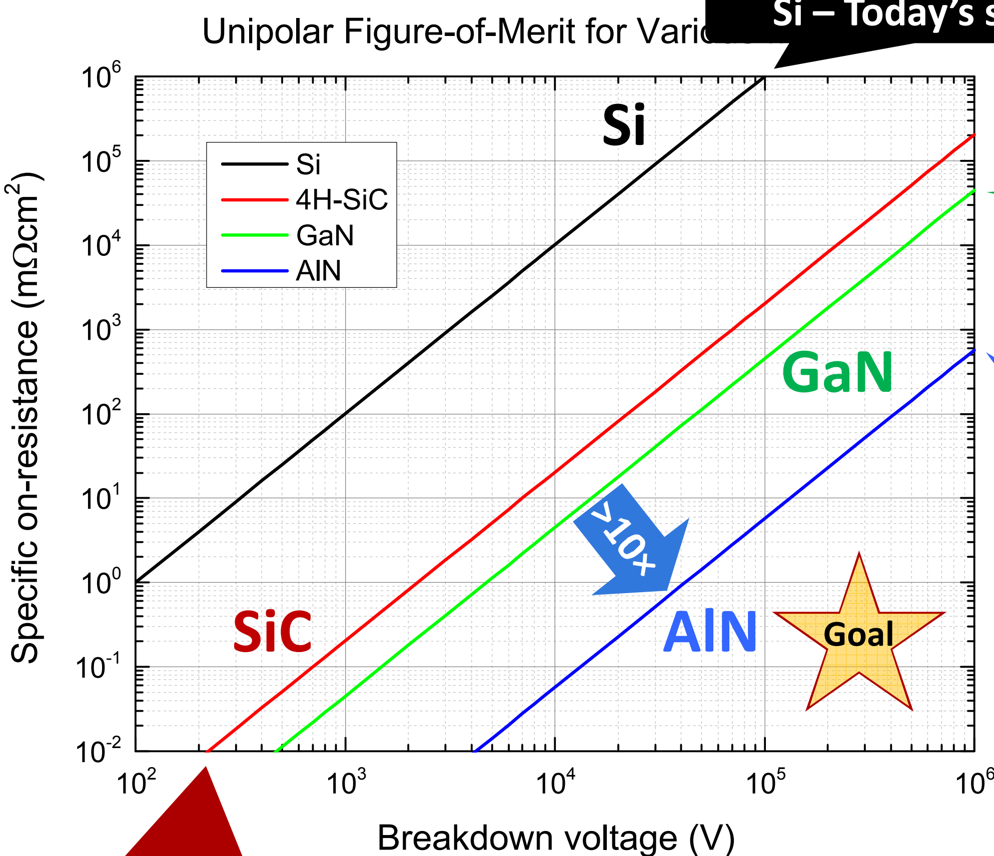
Depends on square of E_C

Strong Dependence of Critical Field on Bandgap



This Grand Challenge Is Developing the Next Generation of Materials for Power Electronics

Si – Today's standard



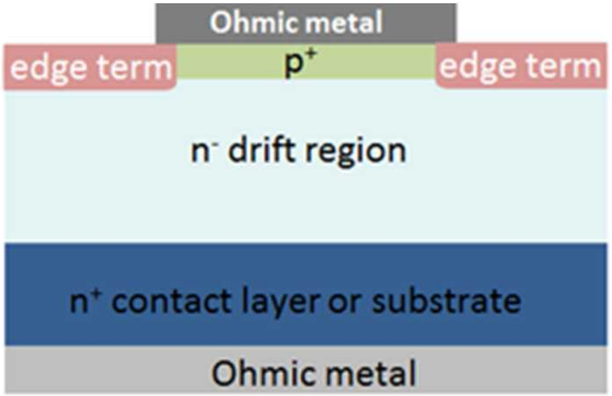
<u>GaN</u>
Lateral devices fairly mature
Vertical devices emerging

<u>AlN</u>
Unexplored space
Unprecedented performance
Numerous challenges!

<u>SiC</u>
Many commercial devices now available

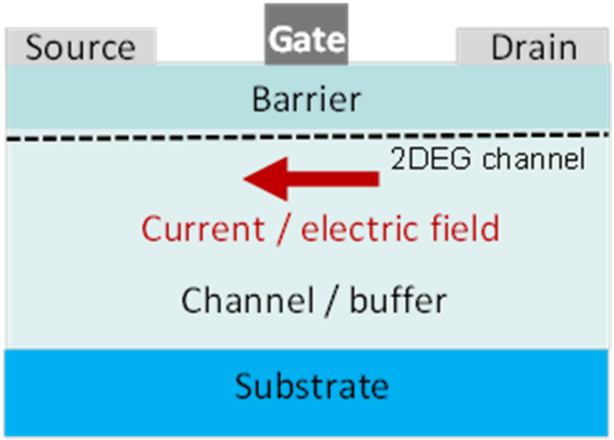
Unique opportunity for SNL and partners to make a foundational contribution to a strategically important field

Two Target Classes of Power Devices



Vertical device (15 kV target)

- Current flow and voltage drop perpendicular to surface
- Architecture is better-suited to high voltage devices
- But native substrates and low doping are challenges



Lateral device (5 kV target)

- Current flow and voltage drop parallel to surface
- Availability of heterostructures and 2DEG is an advantage
- Electric field management is challenging

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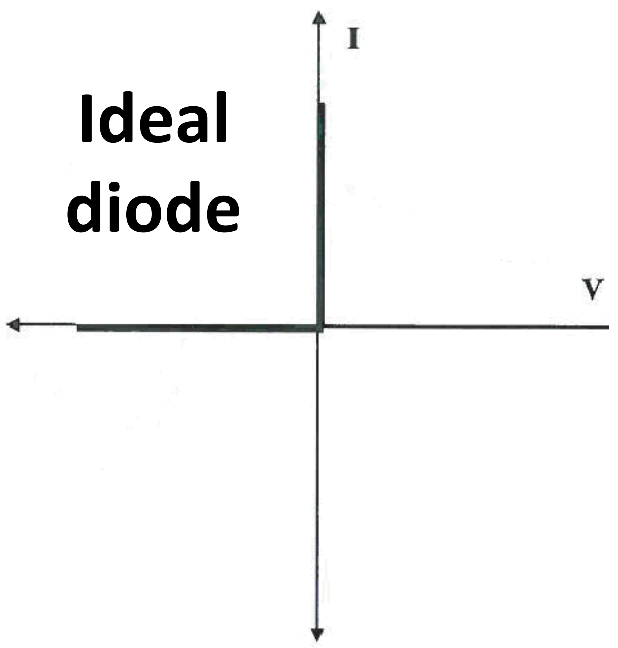
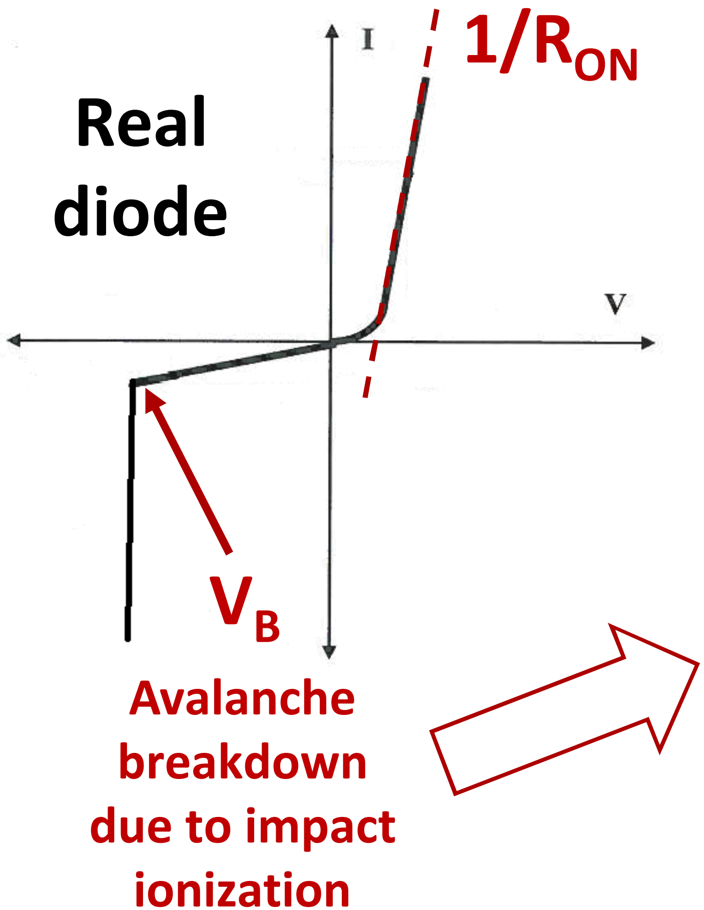
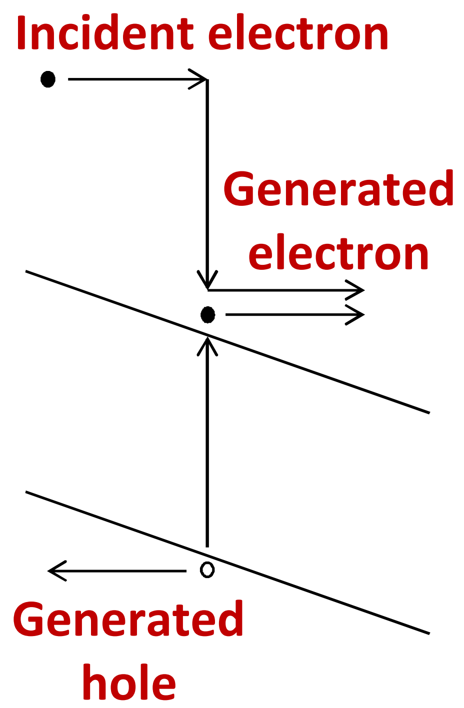
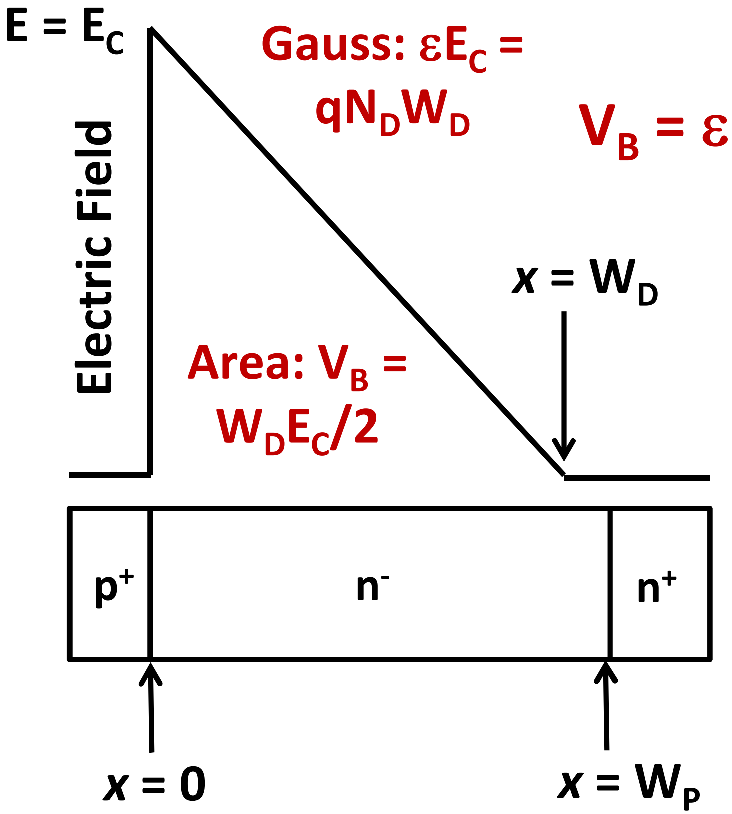
Basics of Power Diodes







Critical Electric Field



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

Number N(*x*) of generated electron-hole pairs obeys

$$\frac{dN}{dx} = (\alpha_p - \alpha_n)N(x)$$

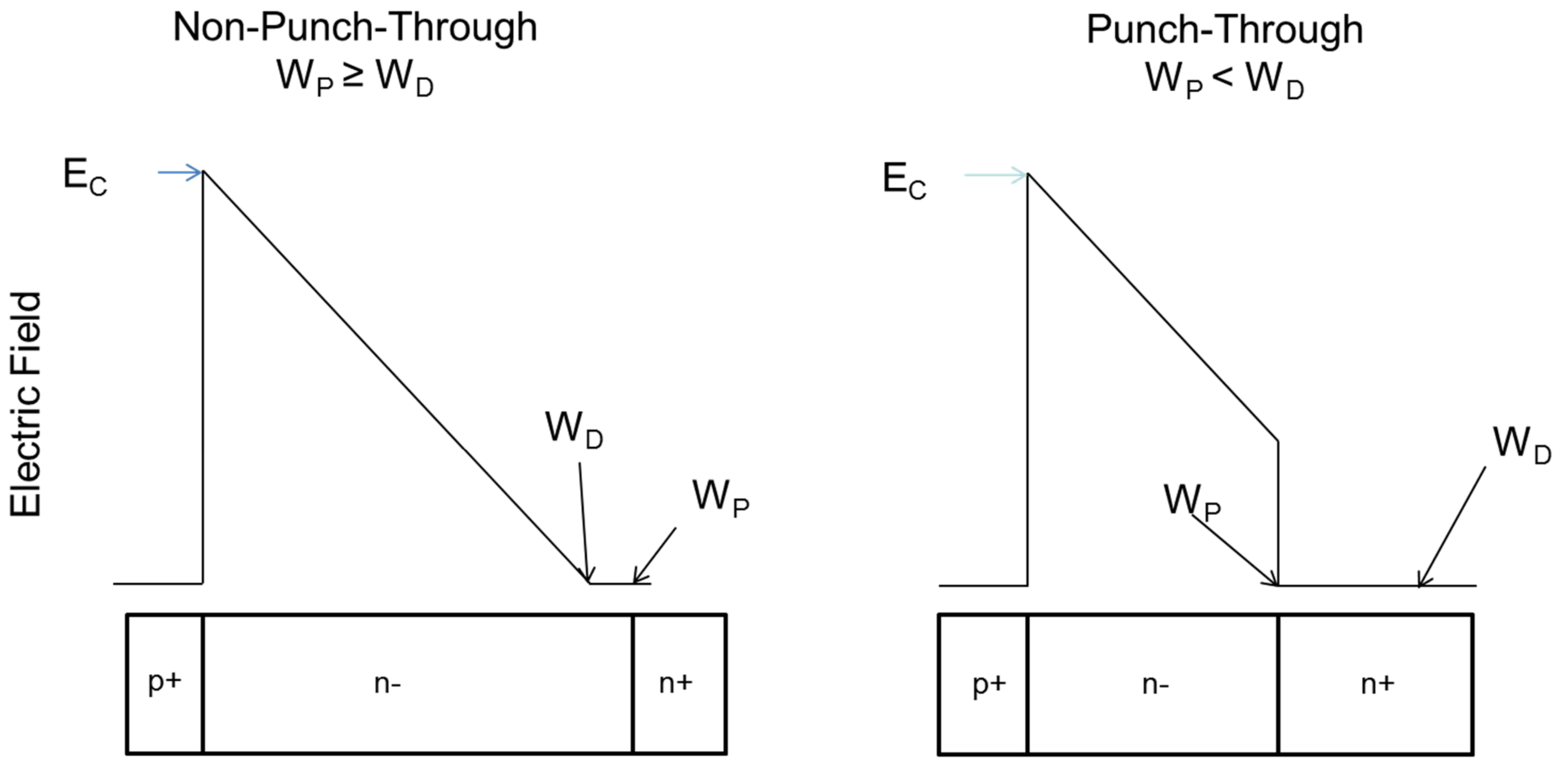
$$\alpha_{n,p} = a_{n,p}\exp\left[-\left(\frac{b_{n,p}}{E}\right)\right]$$

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

Avalanche occurs when denominator approaches infinity

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

Punch-Through vs. Non-Punch-Through Design

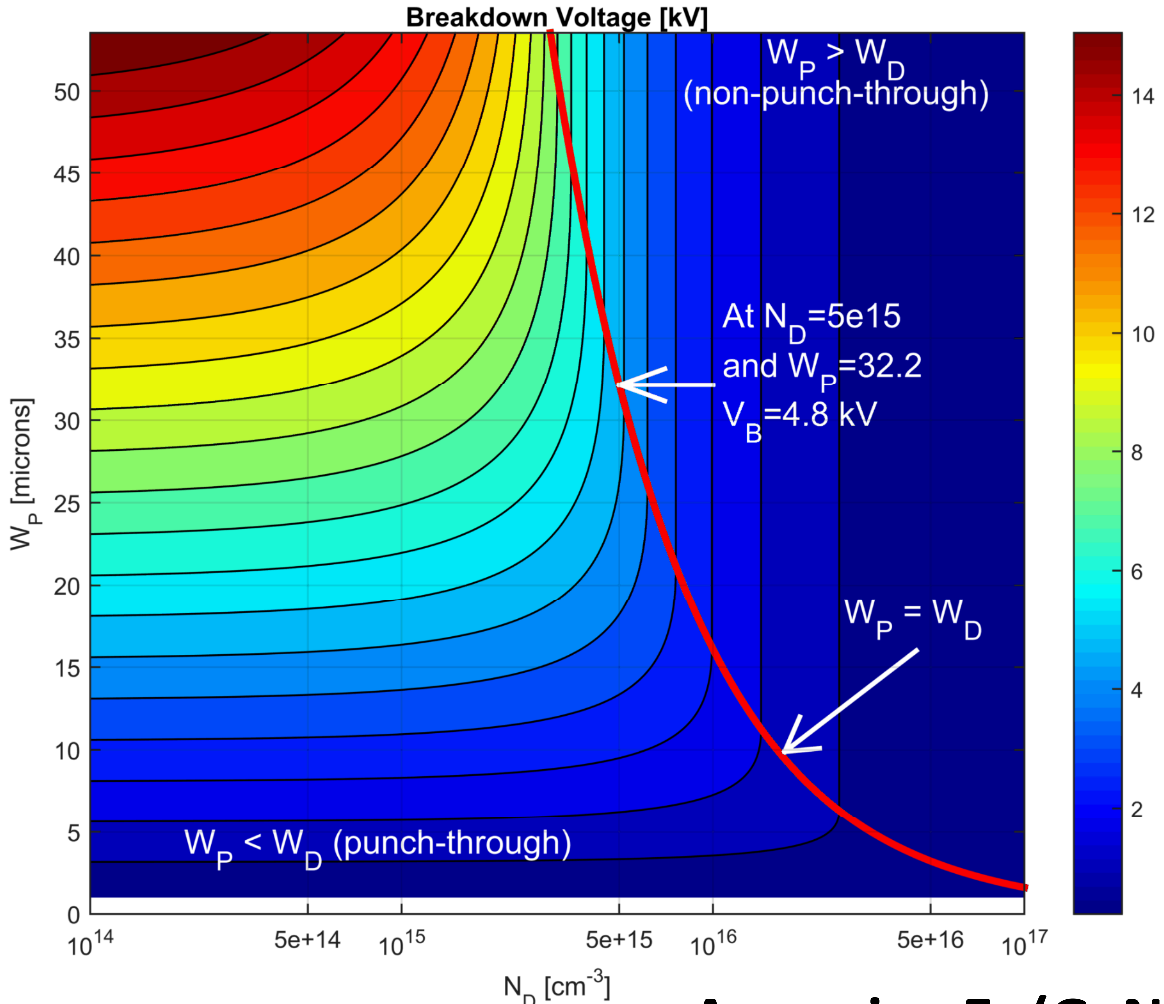


$$V_{br} = \frac{\varepsilon E_C^2}{2qN_D}$$

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

In both cases, low doping is required for high breakdown voltage

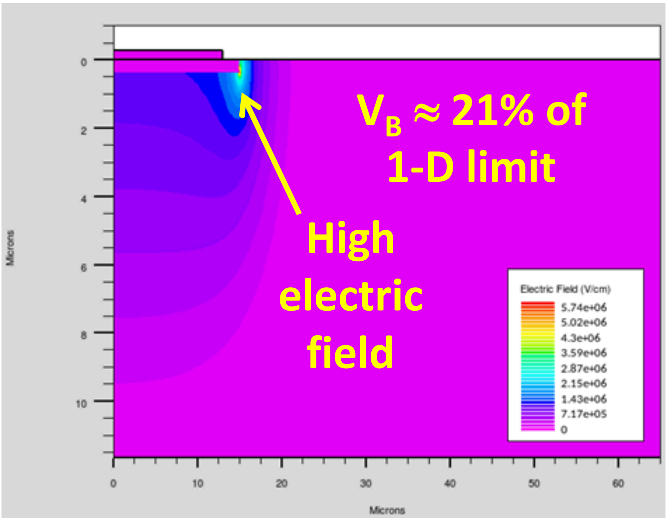
Dependence of V_B on Doping and Layer Thickness

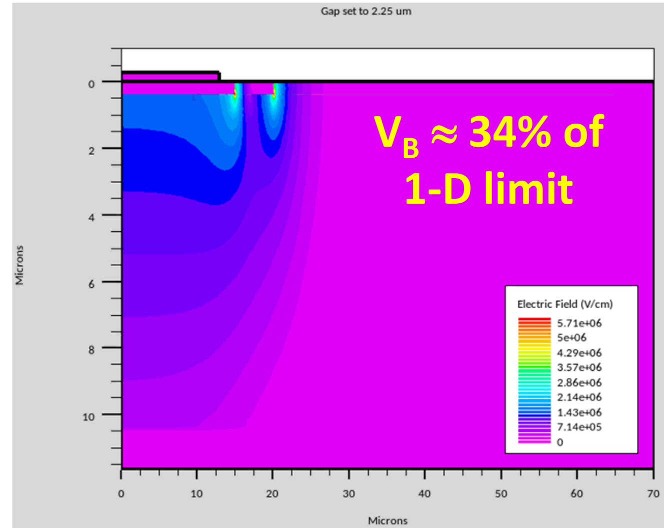


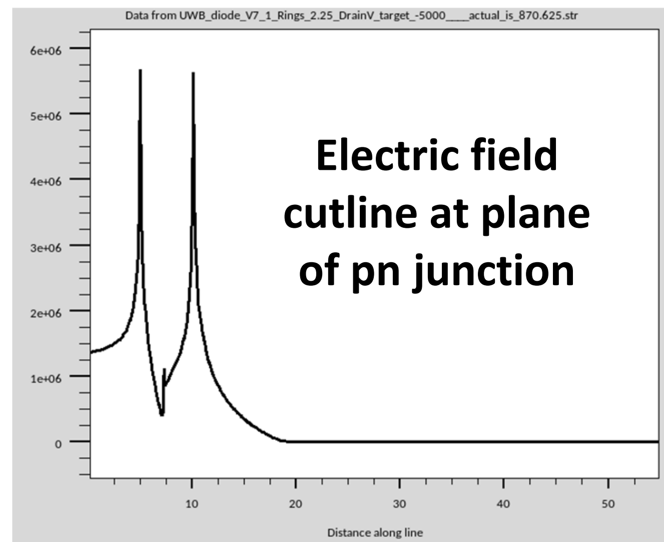
J. Dickerson et al., EMC 2015

Assuming E_C (GaN) = 3.0 MV/cm

Finite Lateral Extent of the Junction Reduces V_B in a Real Device





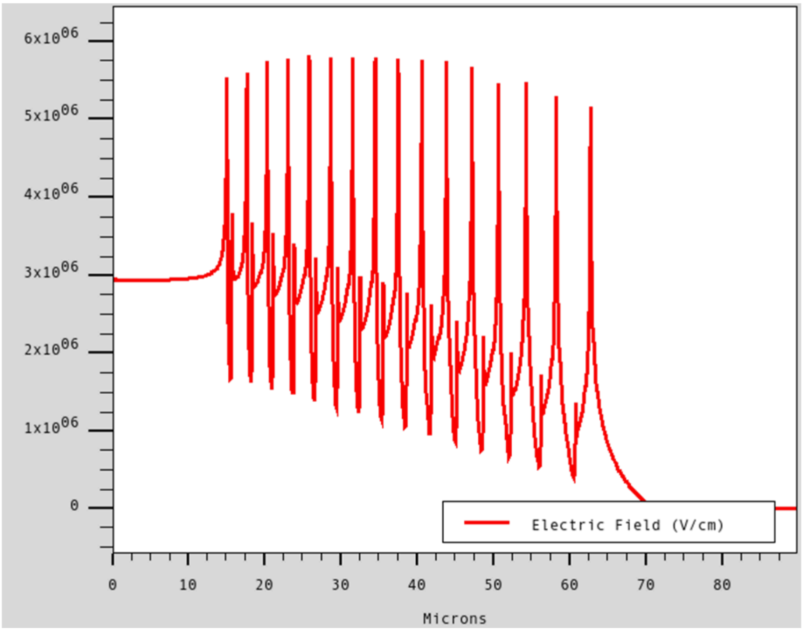


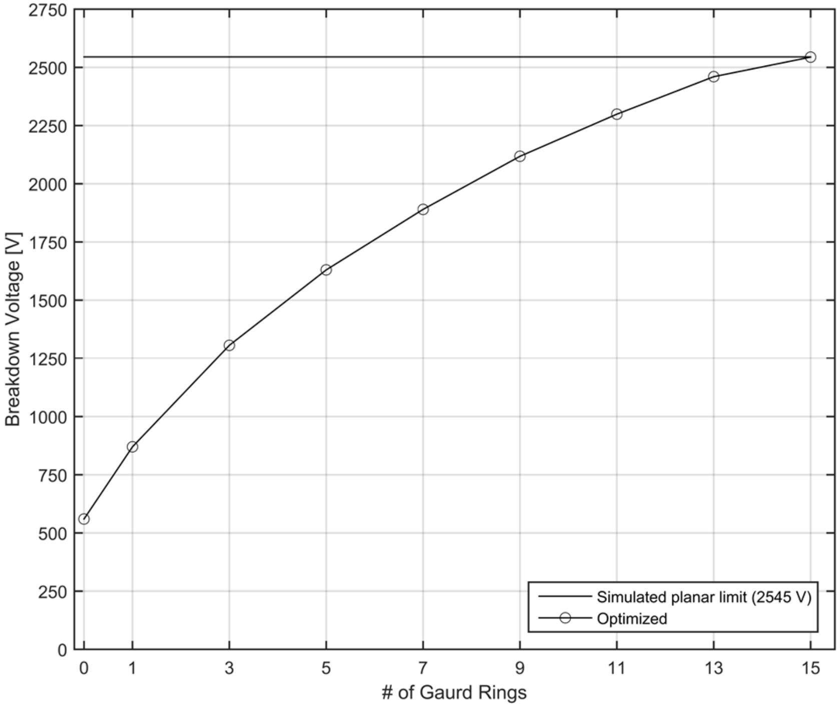
Solution: Implanted guard rings

- N implantation to "deaden" portions of the p^+ epilayer
- Large design space: # of rings, width and spacing of rings, implant dose and depth

J. Dickerson et al., EMC 2015

Optimized Guard Ring Designs

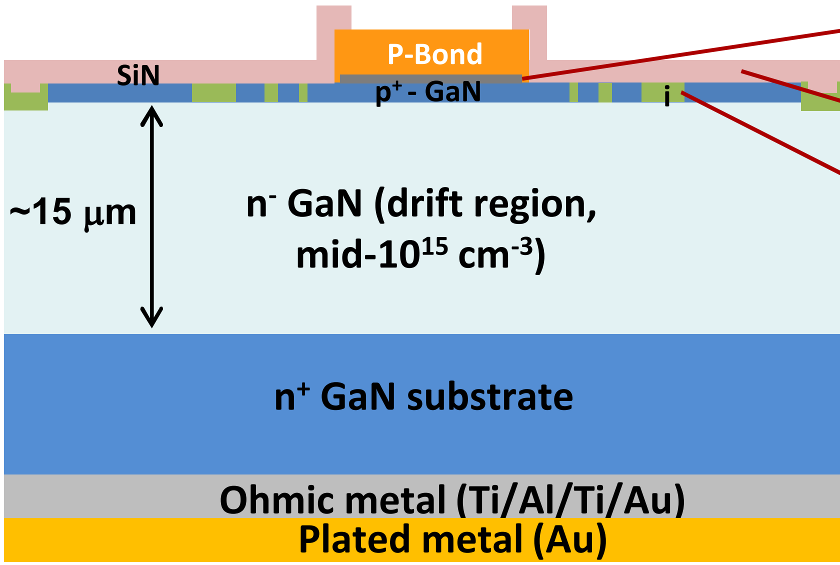




V_B saturates at 1-D limit for 15 optimized guard rings

J. Dickerson et al., EMC 2015

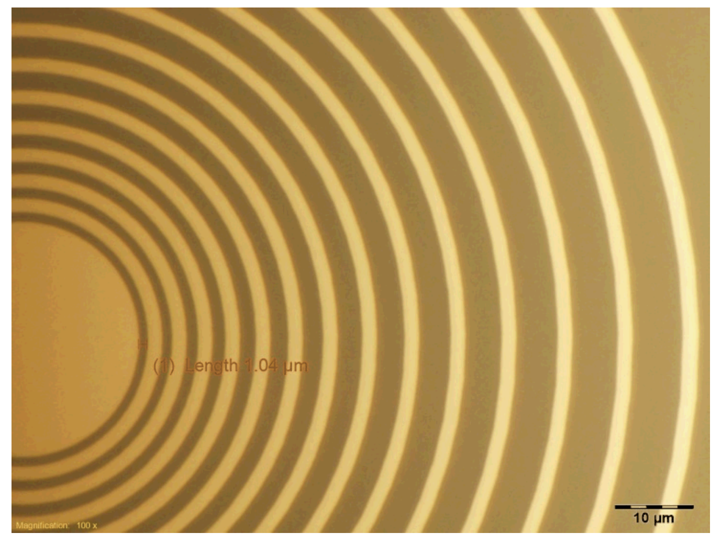
GaN PiN Diode Fabrication



Ohmic p-contact process (Pd/Au)

High breakdown SiN (PECVD, 350°C)

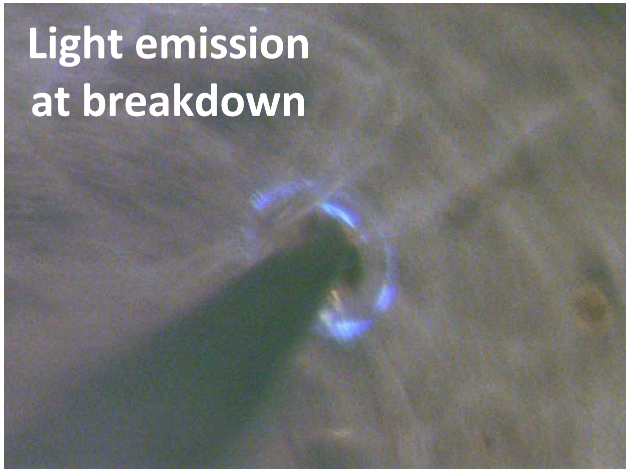
Implantation of guard ring gaps

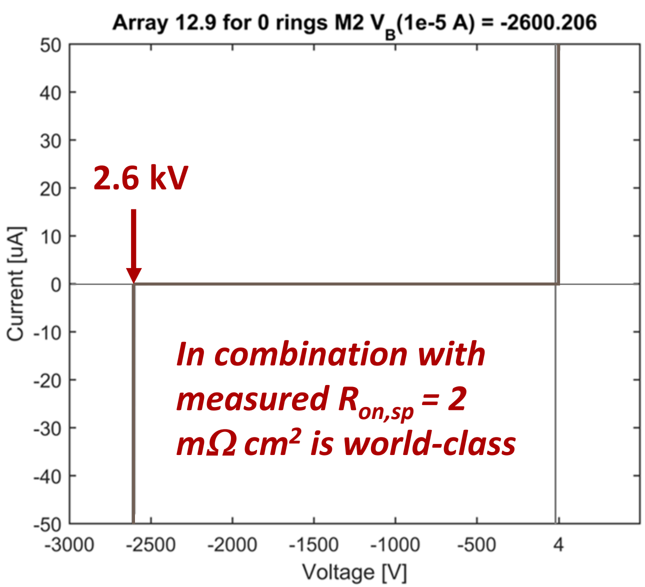


Homoepitaxial GaN growth on GaN substrates!

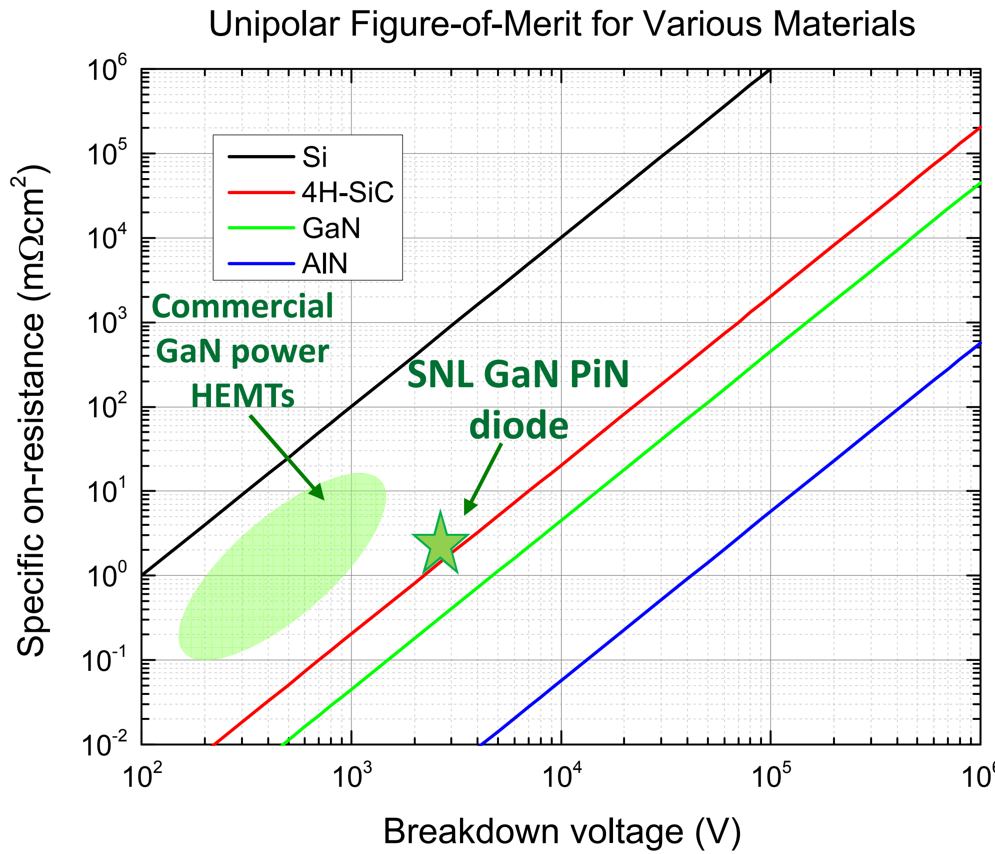
J. Dickerson et al., EMC 2015

GaN PiN Diode Performance





In combination with measured $R_{on,sp}$ = 2 mΩ cm² is world-class

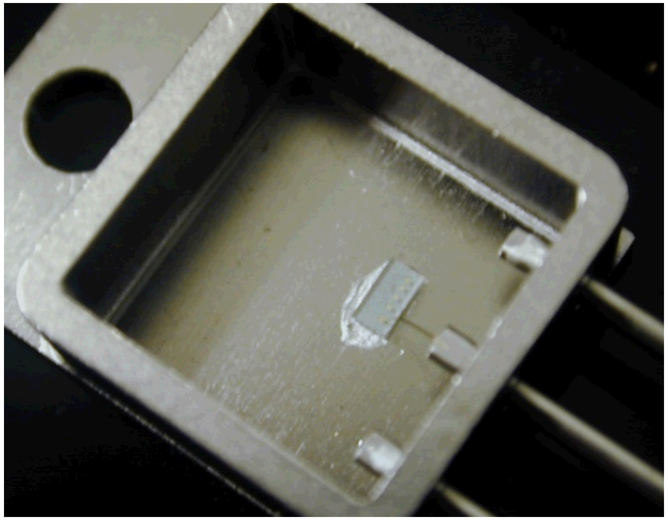


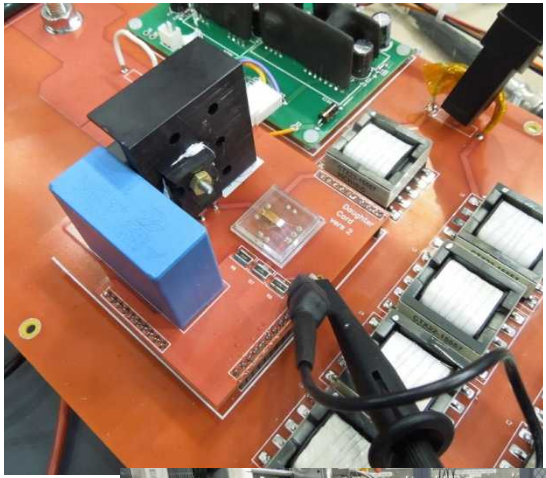
Outstanding results, *but dependence of V_B on # of guard rings does not follow theory!*

- **We have an explanation, is now being verified**

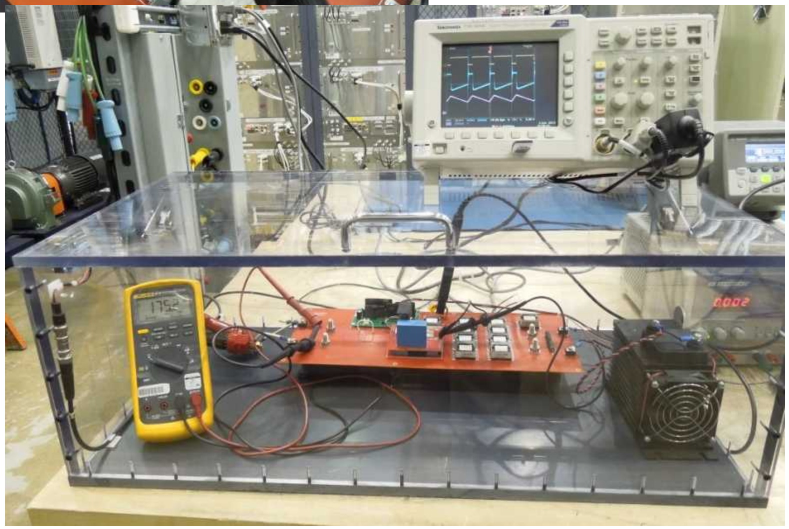
J. Dickerson et al., EMC 2015

Packaging and Switching Characterization of GaN PiN Diodes

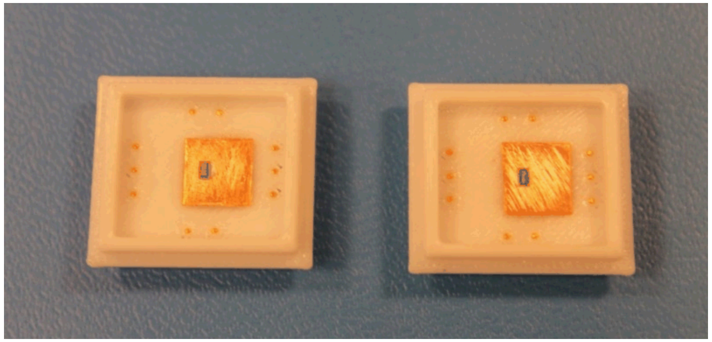




Switching test characterization



Commercial and custom in-house device packaging



J. Neely

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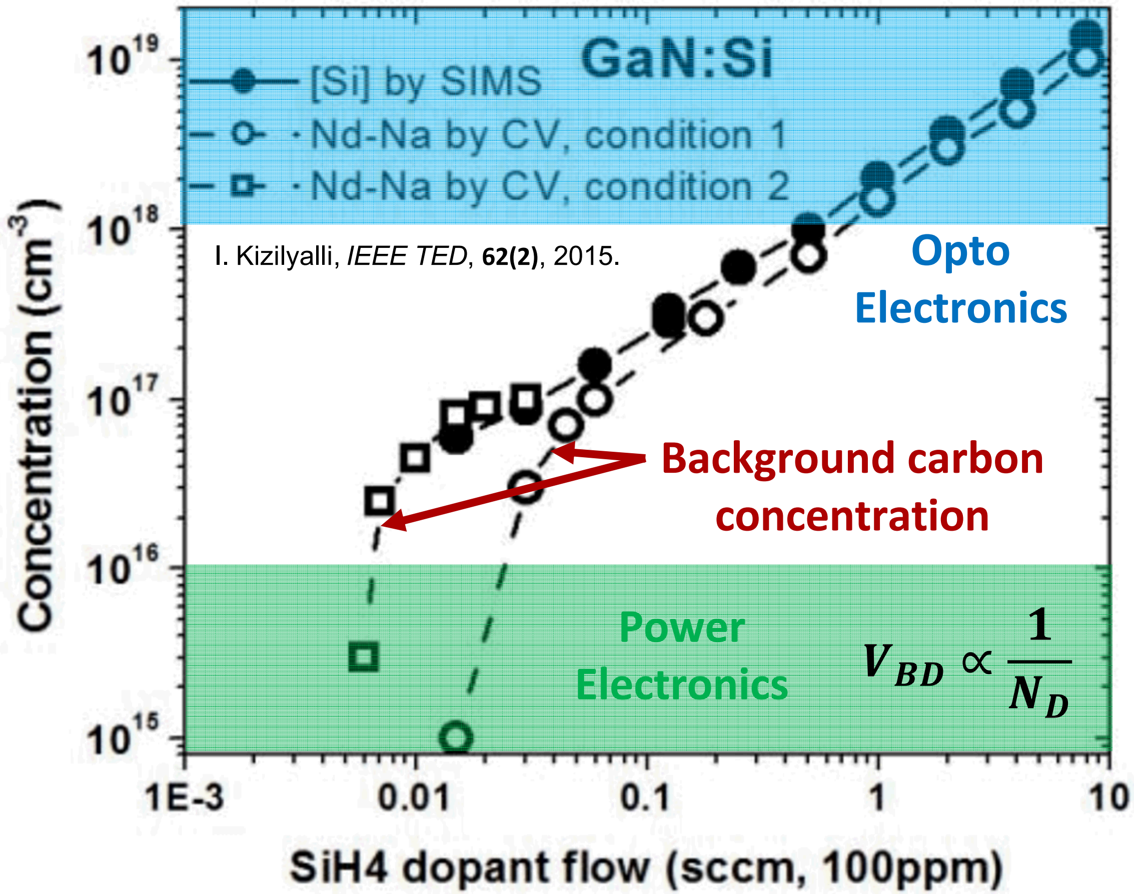
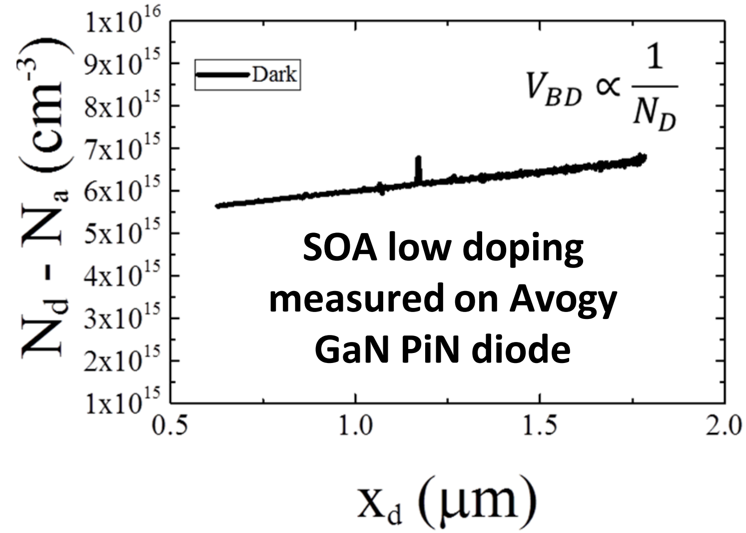
Low Doping in GaN Drift Regions

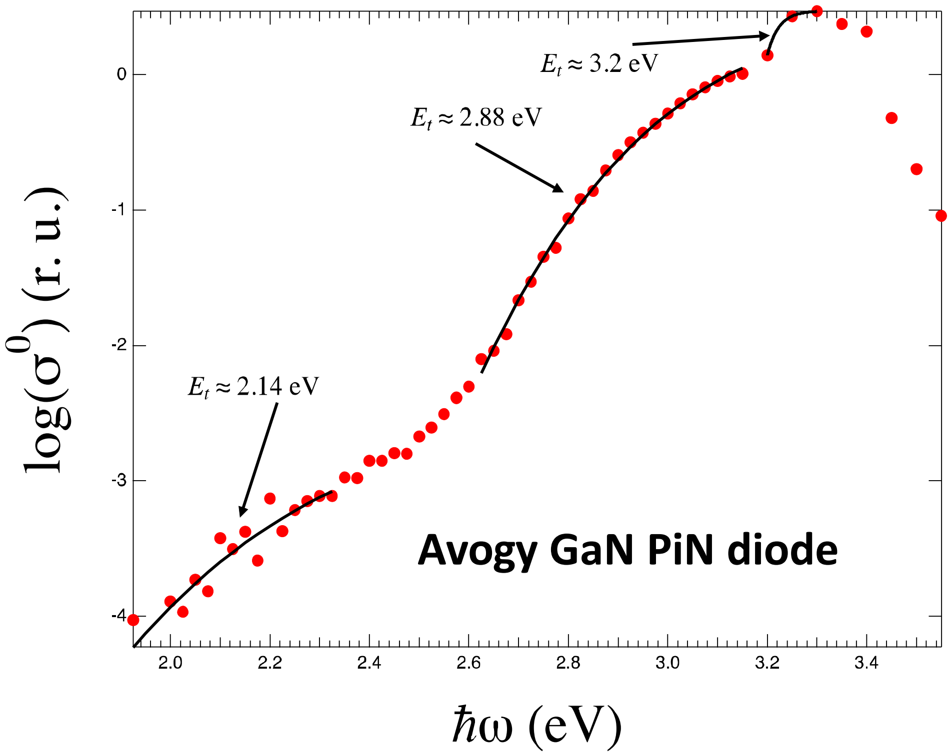




For GaN drift regions, the background acceptor concentration may be the same order of magnitude as the intentional dopant concentration!

M. P. King et al., EMC 2015

DLOS Spectrum of Homoepitaxial GaN Drift Region



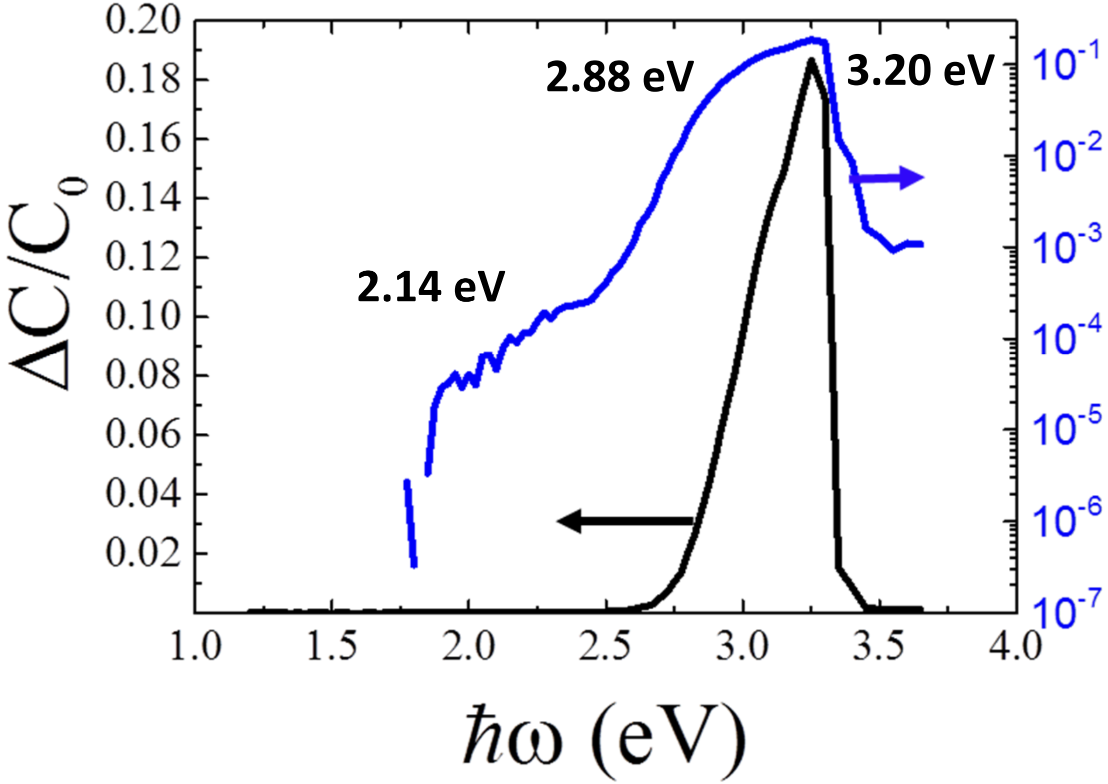
Direction of increasing energy below conduction band

- **DLOS studies show three prominent defect levels at:**
  - **E_C - 2.14 eV**
  - **E_C - 2.88 eV**
  - **E_C - 3.20 eV**
- **States at E_C - 2.14 eV and E_C - 2.88 eV are broad, indicating strong lattice relaxation following carrier emission**

M. P. King et al., EMC 2015

Steady-State Photocapacitance

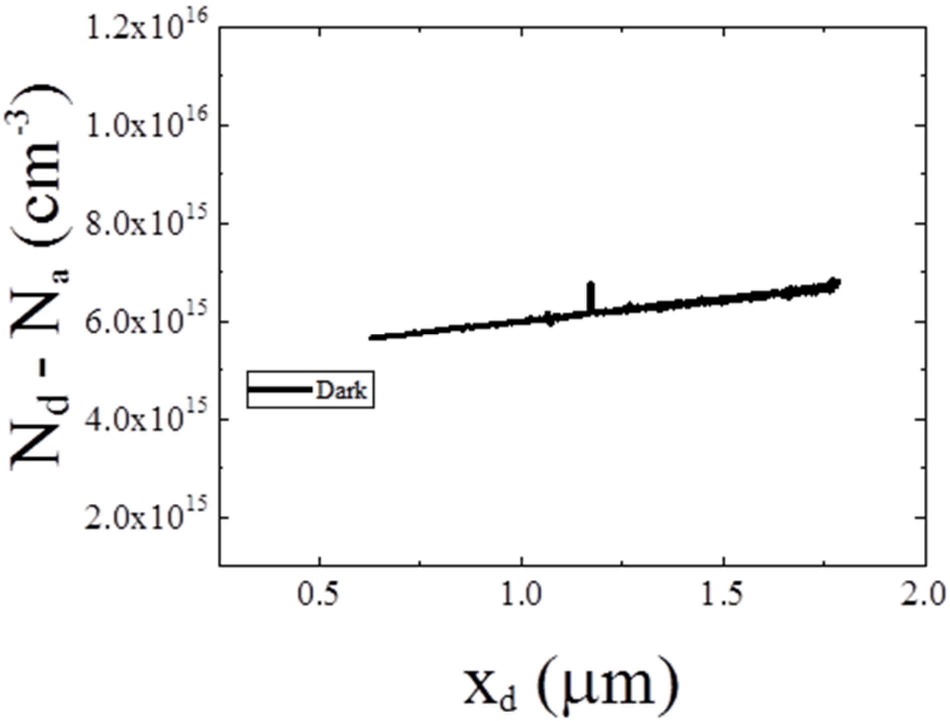
Provides defect density information

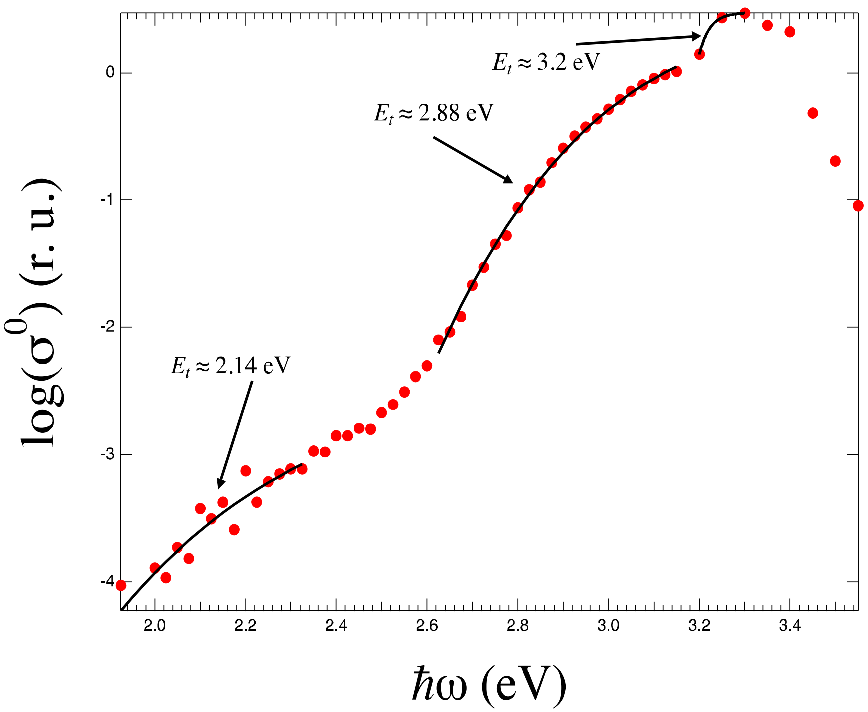


- **States at E_C - 2.14 eV and E_C - 2.88 eV are again broad**
- **Defect level at E_C-2.14 eV shows small impact on response**
- **Levels at E_C - 2.88 eV and E_C - 3.20 eV are observed to be large in magnitude and *are likely primary compensating centers***

M. P. King et al., EMC 2015

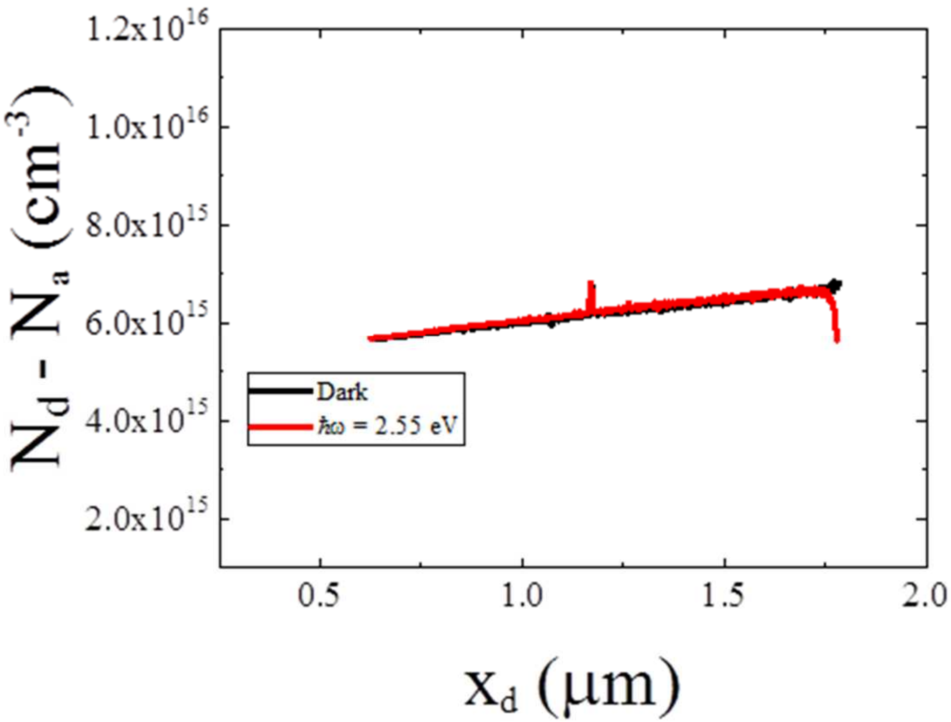
Lighted CV Correlates with DLOS to Determine Compensating Defect Density

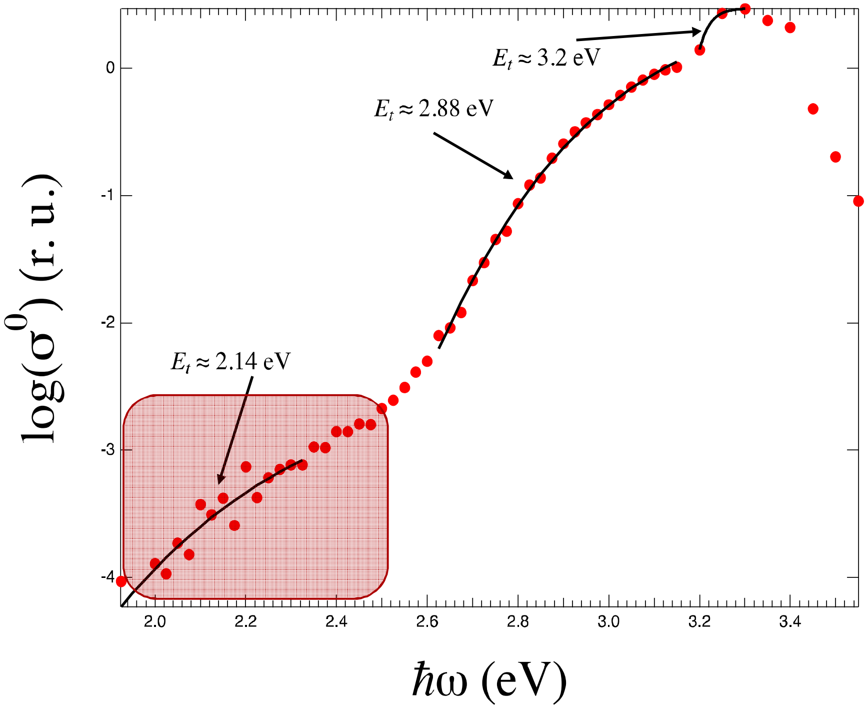




M. P. King et al., EMC 2015

Lighted CV Correlates with DLOS to Determine Compensating Defect Density

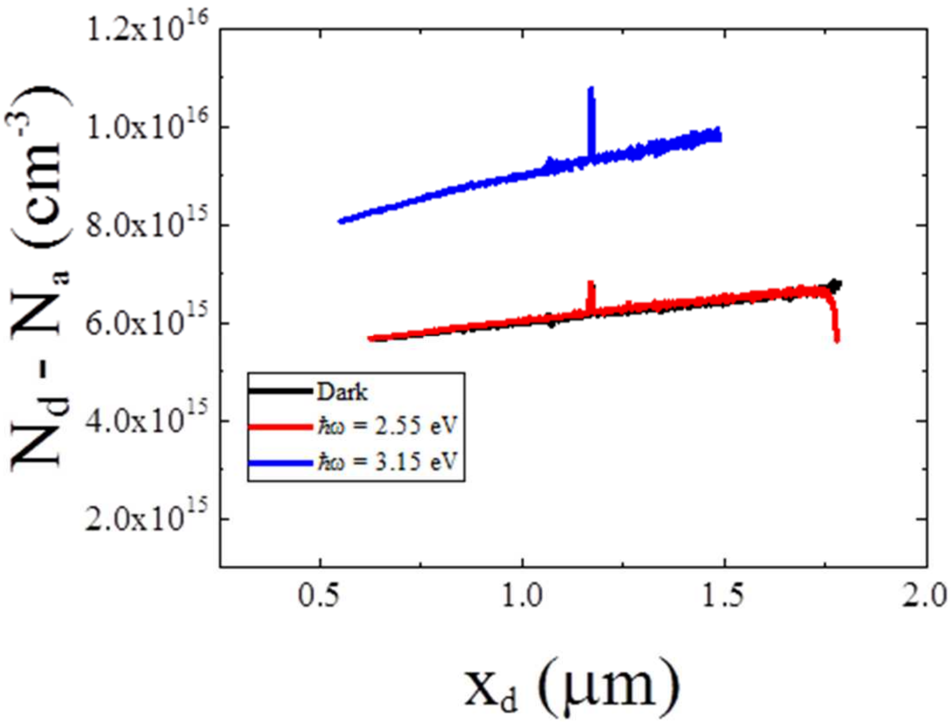


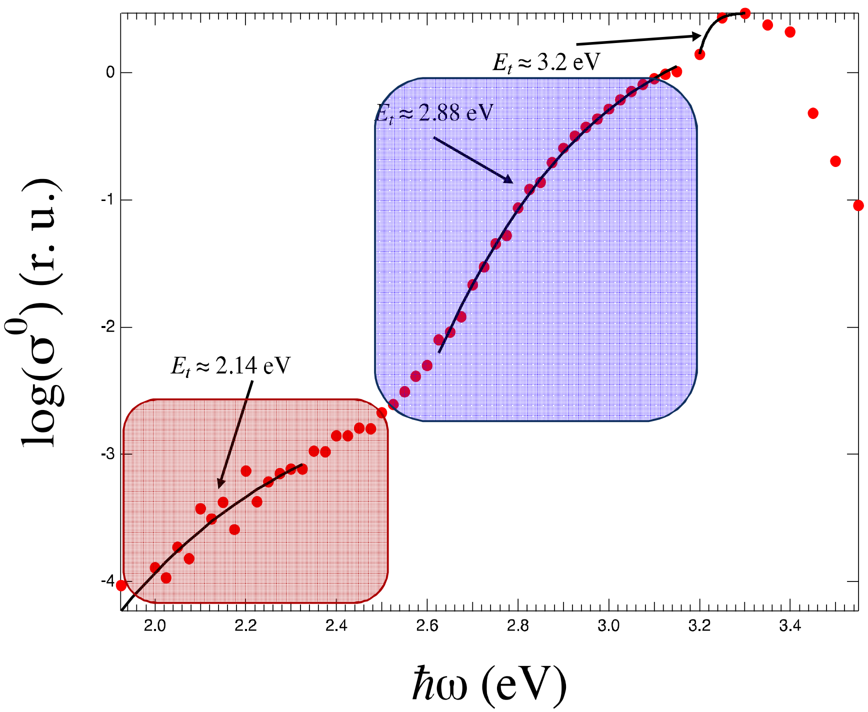


- **Small response from E_C – 2.14 eV level, $N_T \approx 3\times10^{13}$ cm^{-3}**

M. P. King et al., EMC 2015

Lighted CV Correlates with DLOS to Determine Compensating Defect Density

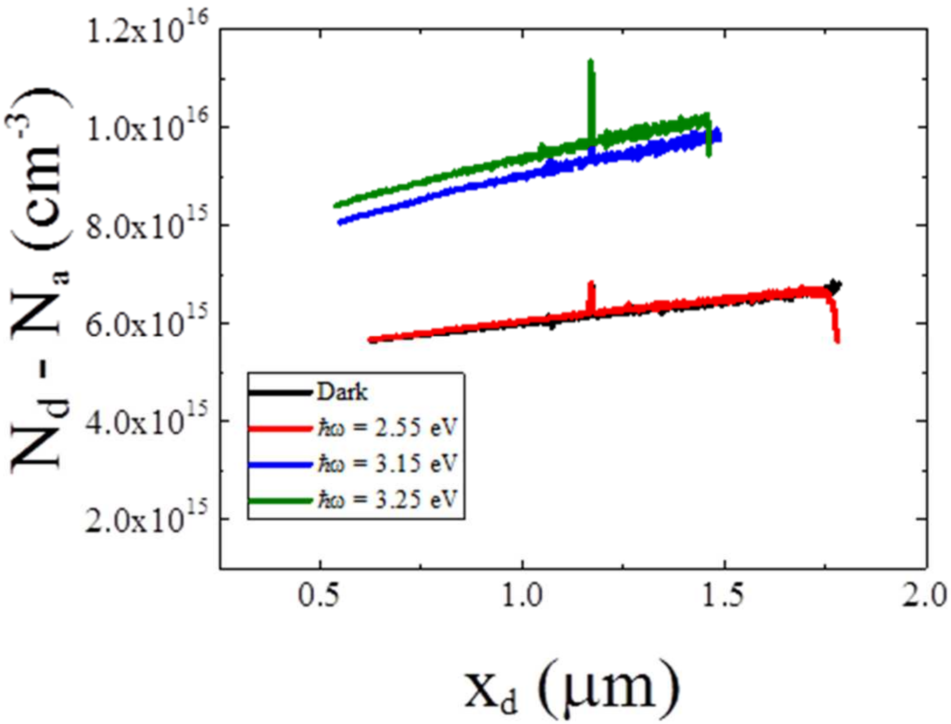


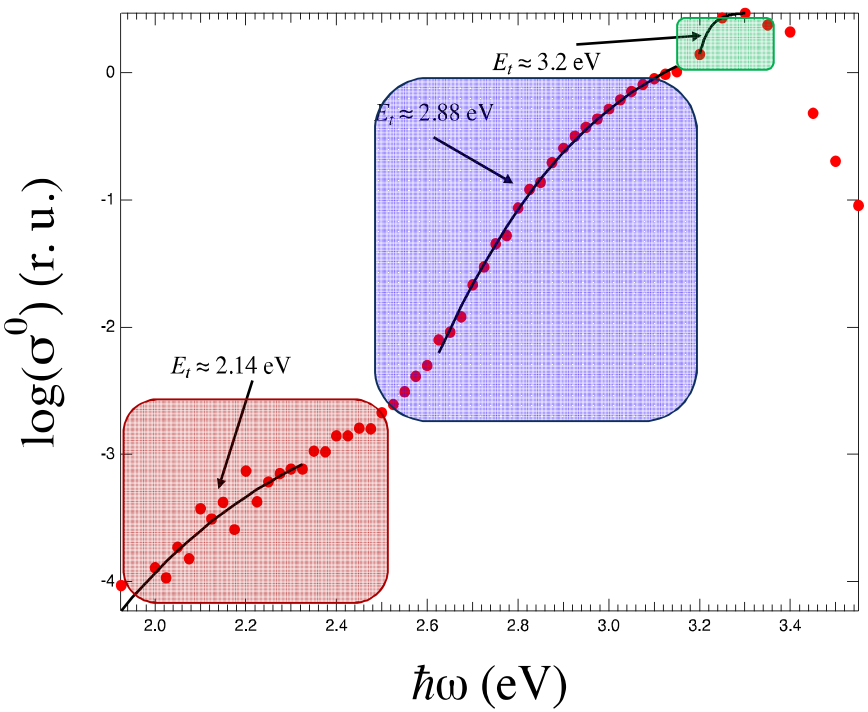


- **Small response from E_C – 2.14 eV level, $N_T \approx 3\times10^{13}$ cm^{-3}**
- **E_C - 2.88 eV level is the primary compensating defect, $N_T \approx 2\times10^{15}$ cm^{-3}**

M. P. King et al., EMC 2015

Lighted CV Correlates with DLOS to Determine Compensating Defect Density





- Small response from E_C – 2.14 eV level, $N_T \approx 3\times10^{13}$ cm^{-3}
- E_C - 2.88 eV level is the primary compensating defect, $N_T \approx 2\times10^{15}$ cm^{-3}
- E_C – 3.20 eV level is on order of free carrier concentration, $N_T \approx 2.5\times10^{15}$ cm^{-3}

M. P. King et al., EMC 2015

Outline

- **Introduction and motivation**
  - Introduction to Sandia
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- **Vertical devices**
  - GaN PiN diode design and fabrication
  - Doping and defect physics in GaN drift regions
  - $Al_{0.3}Ga_{0.7}N$ PiN diodes
- **Lateral devices**
  - Al-Rich $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ heterostructures

Problem: No Lattice-Matched Conducting Substrate!

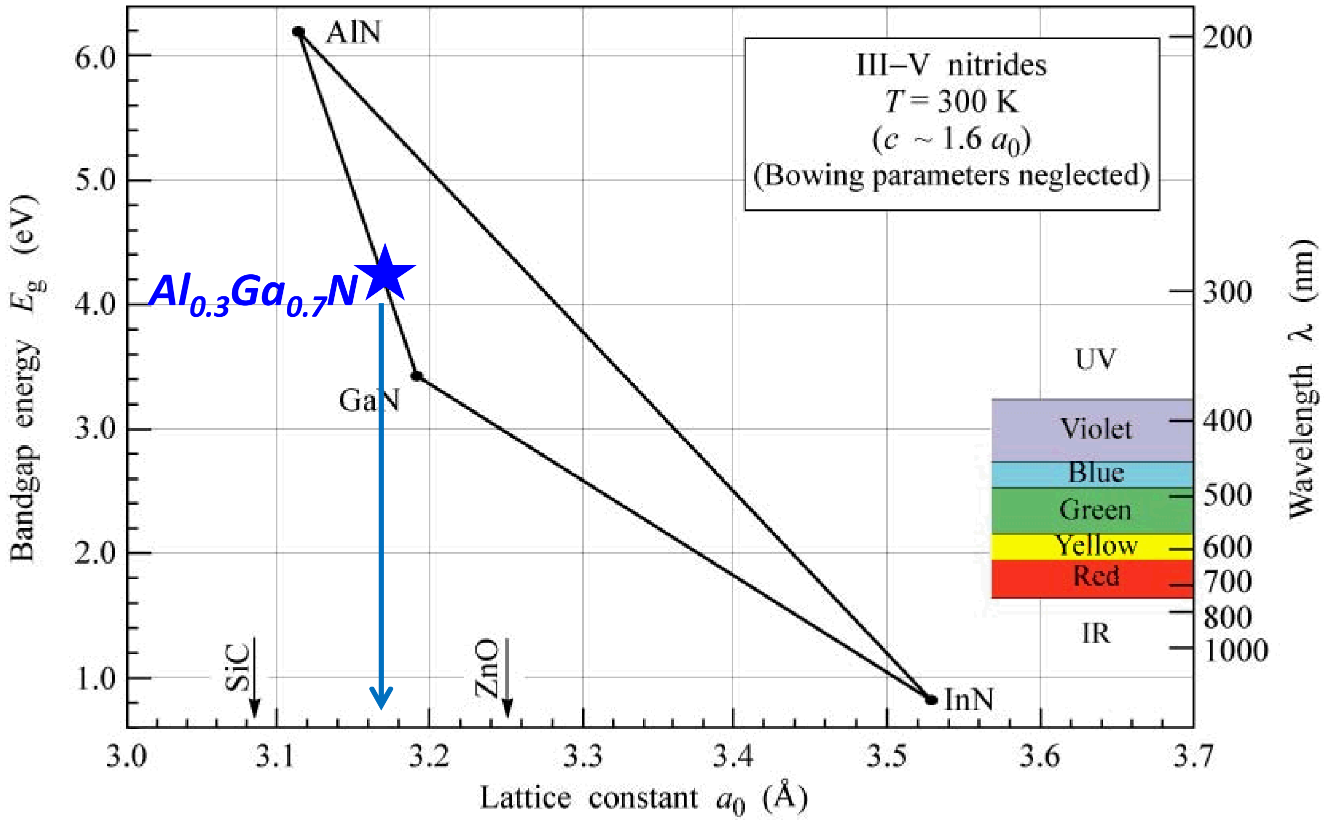


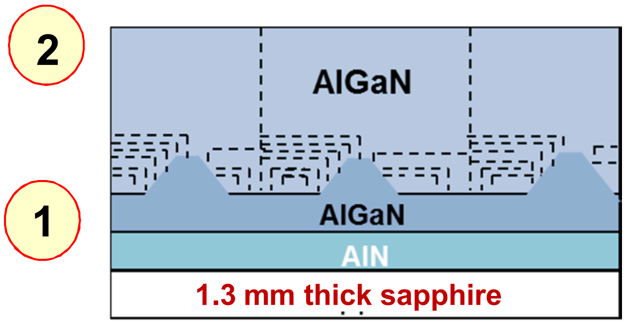
Fig. 12.12. Bandgap energy versus lattice constant of III–V nitride semiconductors at room temperature.

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

AlGaN Overgrowth of Patterned Templates on Thick Sapphire

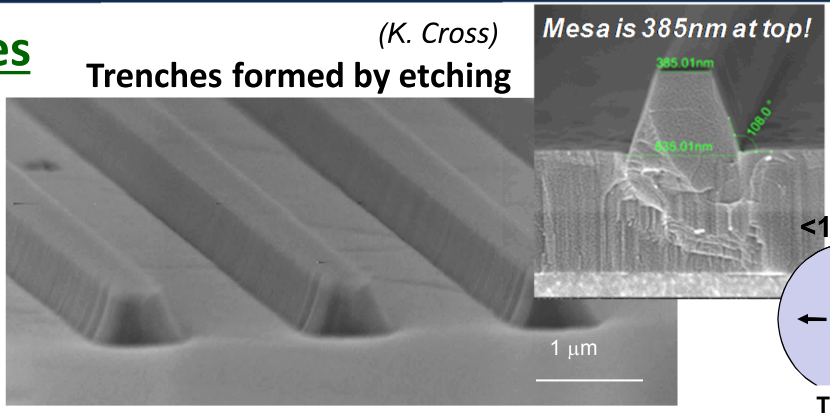
AlGaN Growth on Patterned Templates

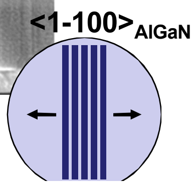
AlGaN with reduced dislocations



(K. Cross)

Trenches formed by etching



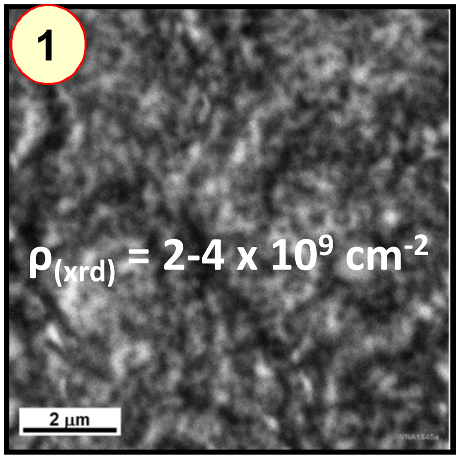


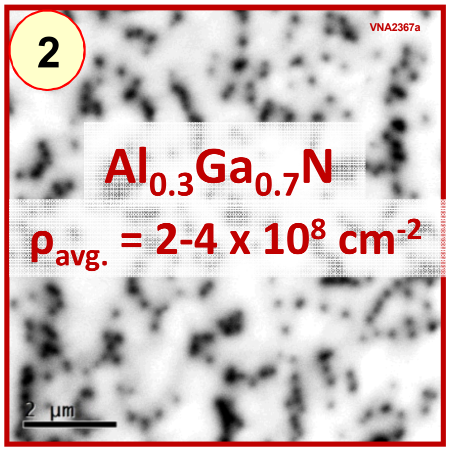
Trench Alignment

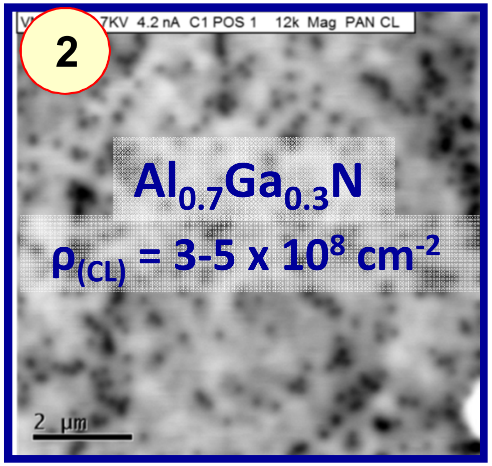
➡ ***Sub-micron features are key innovation for uniform reduction of dislocations***

Cathodoluminescence

(L. Alessi)





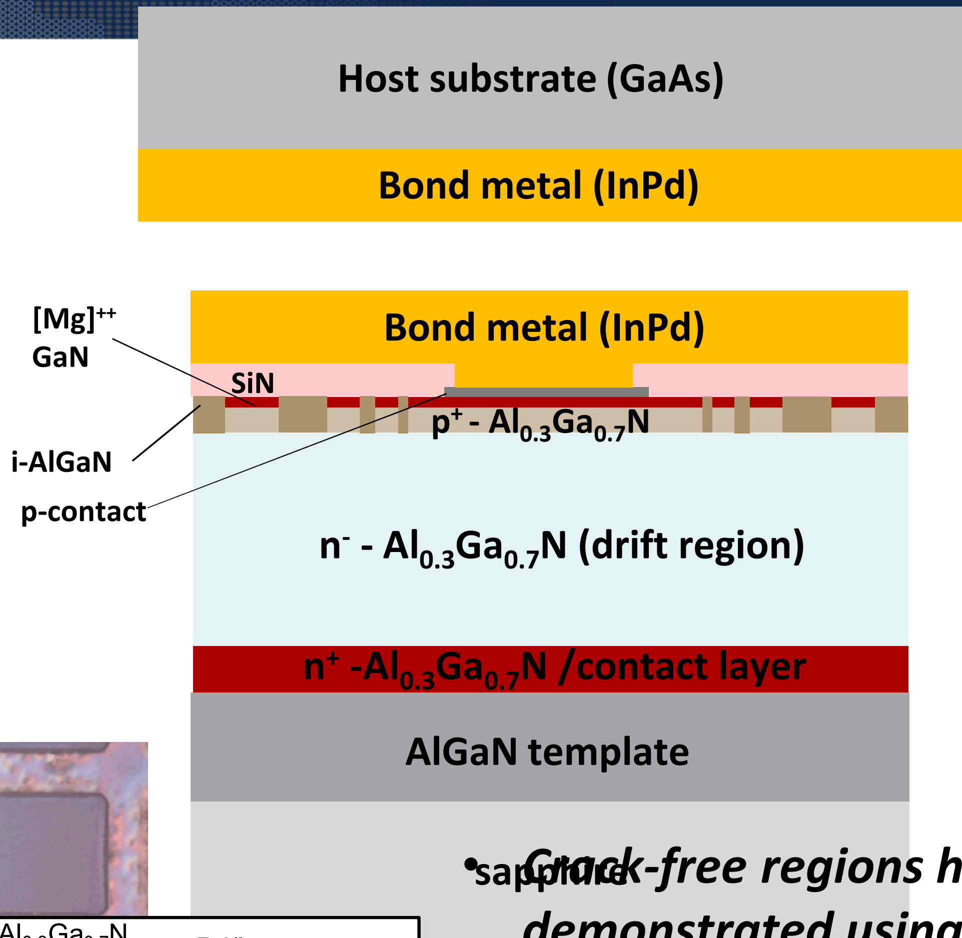


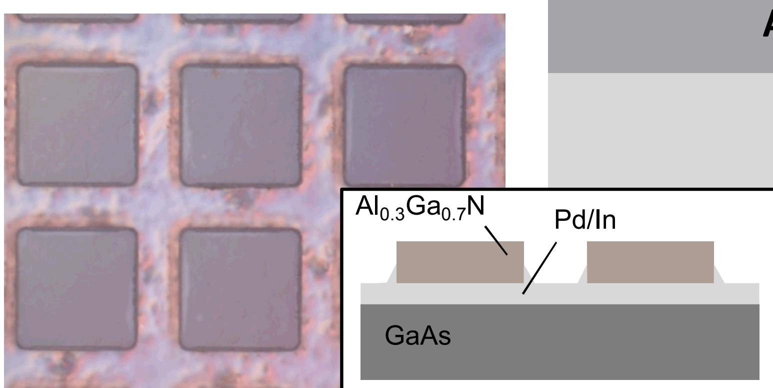
A. Allerman et. al., JCG 2014

10-20x reduction

10-15x reduction

$Al_{0.3}Ga_{0.7}N$ PiN Diode Processing





- *Crack-free regions have been demonstrated using laser lift-off of $Al_{0.3}Ga_{0.7}N$ epitaxial layers from AlN/sapphire templates*

…imer laser (> 1 J/cm²)

J. Wierer

Outline

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Target Metrics for 5 kV UWBG HEMT

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

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

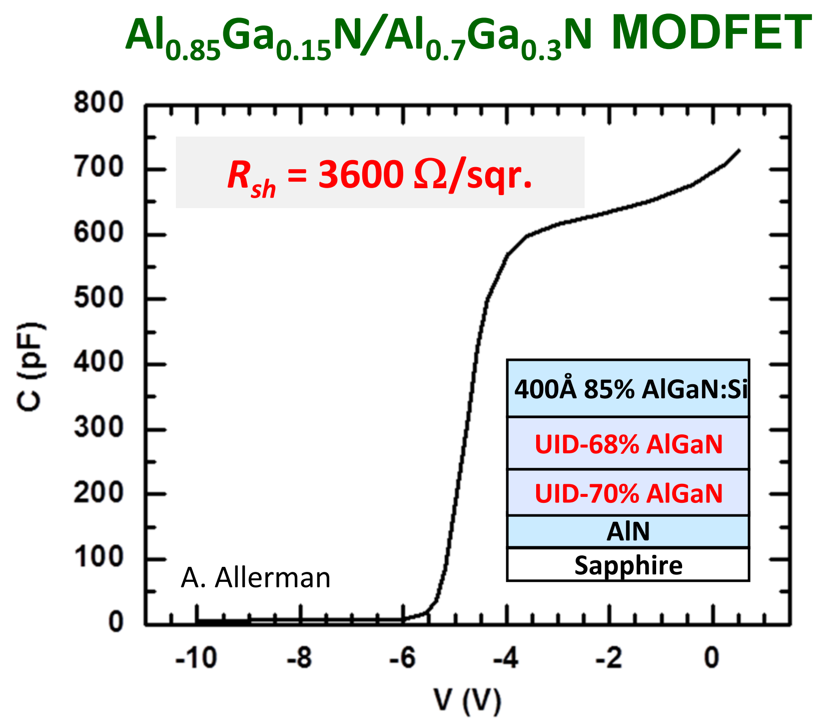
$$V_B = E_{crit} L_{gd}$$

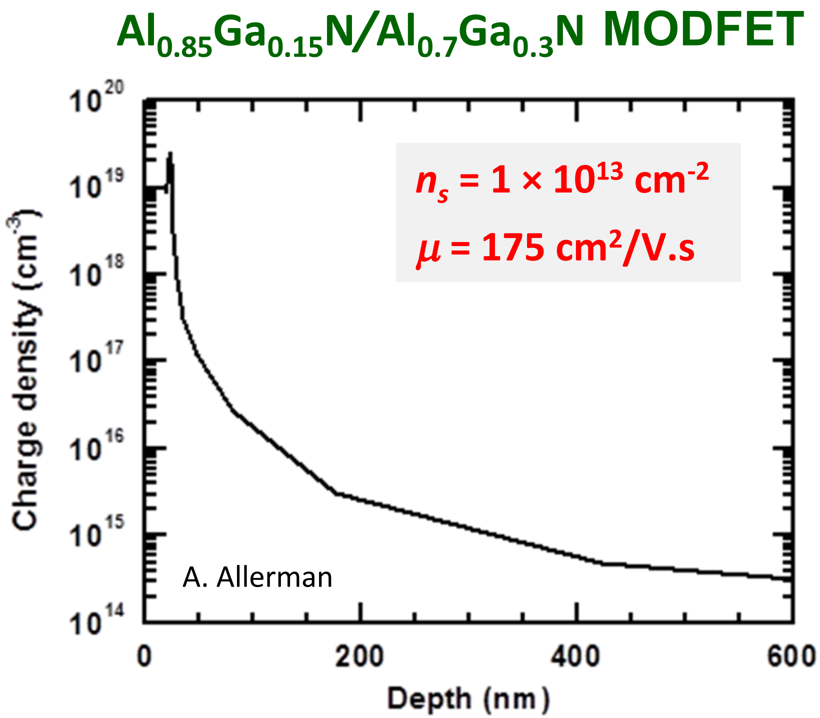
$$V_{th} = \frac{\phi_B}{q} - \frac{\Delta E_c}{q} - \frac{n_s d}{\epsilon}$$

- 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_{crit} = 4 MV/cm (effective value)
- V_T > +3 V
  - ϕ_B = 4 eV

A. Armstrong et al., ICMAT 2015

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

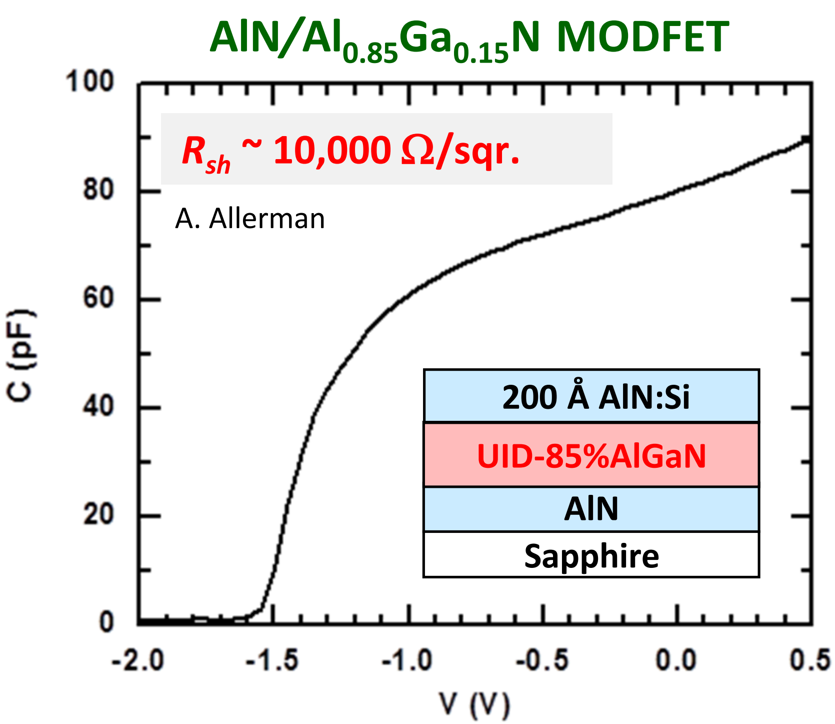


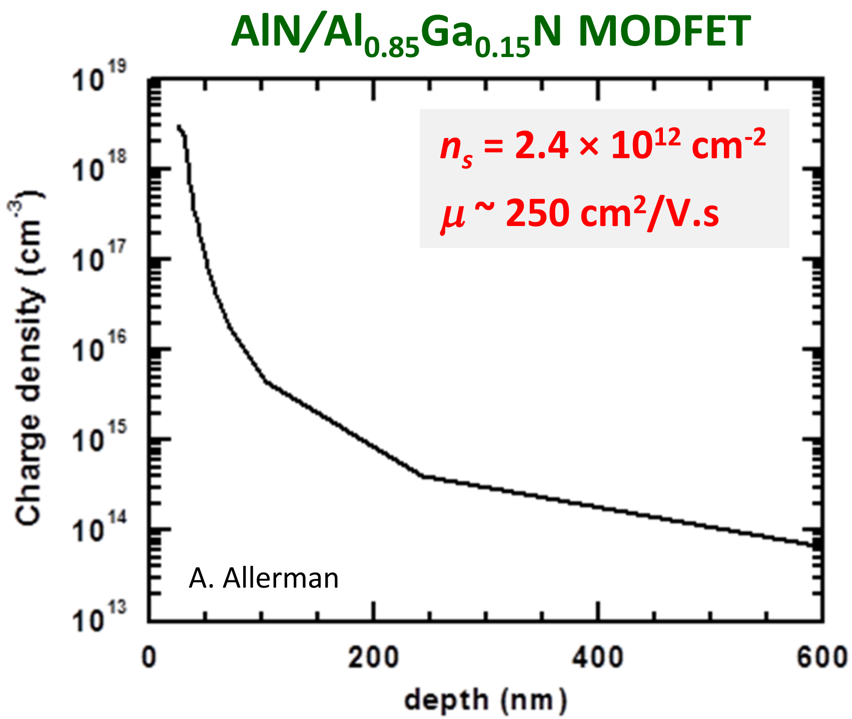


- First demonstration of 2DEG in $Al_xGa_{1-x}N$ channel for $x > 0.6$
- Achieved $\boldsymbol{n_s = 1 \times 10^{13}}$ **cm**$^{-2}$, $\boldsymbol{\mu}$ **= 175 cm**^{2}**/V.s** in $Al_{0.7}Ga_{0.3}N$ channel

A. Armstrong et al., ICMAT 2015

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

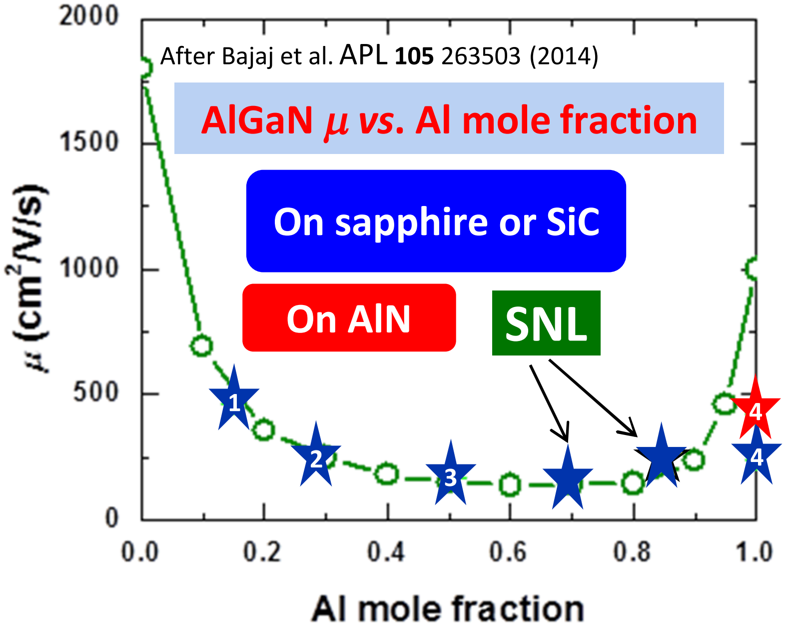




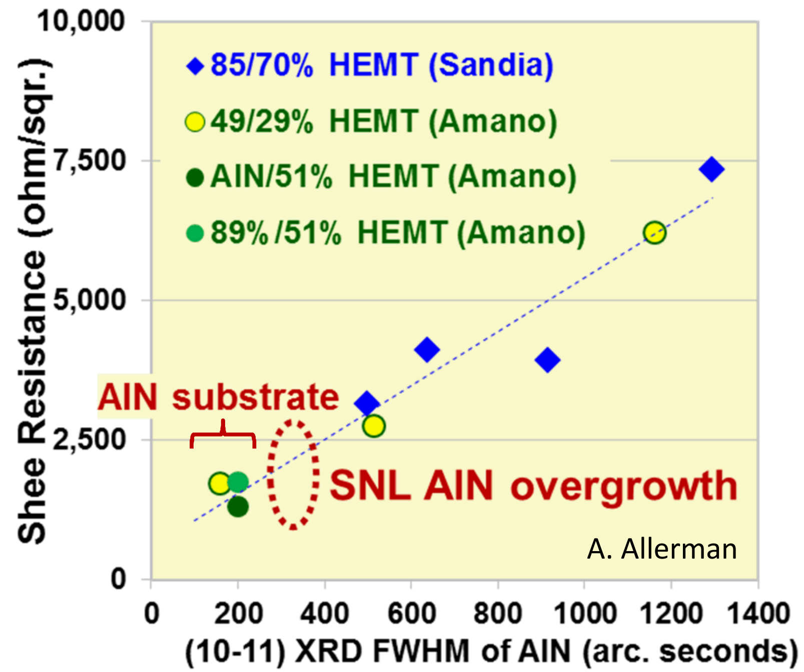
- Achieved n_s = 2.4 × 10^{12} cm^{-2}, μ ~ 250 cm^2/V.s in $Al_{0.85}Ga_{0.15}N$ channel
- Largest Al mole fraction exhibiting 2DEG

A. Armstrong et al., ICMAT 2015

Challenge: Channel Mobility and Sheet Resistance



1. Nanjo et al. IEEE TED **60** 1046 (2013)
2. Hashimoto et al. SEI Tech. Rev. **71** 83 (2010)
3. Hashimoto et al. PSSA **209** 501 (2012)
4. Taniyusa et al. APL **89** 182112 (2006)



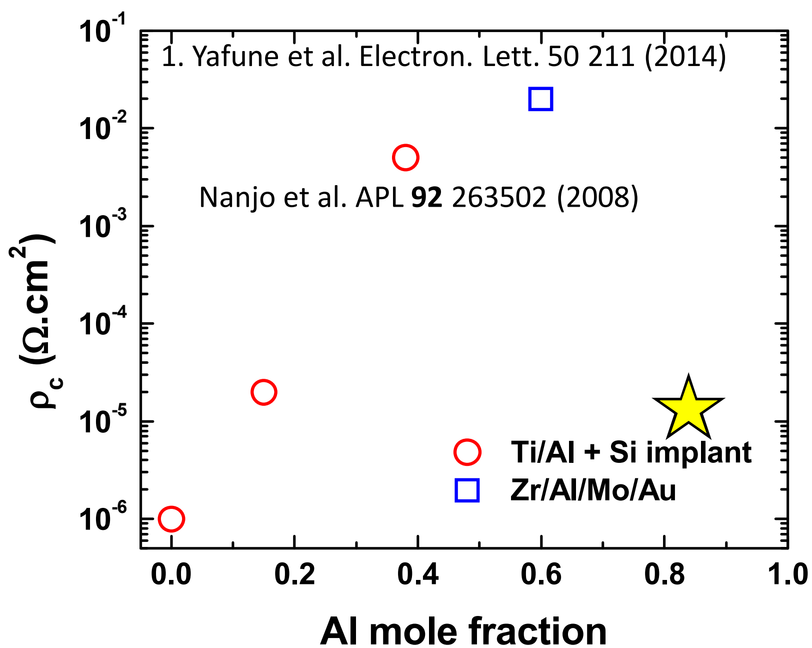
Hashimoto et al. SEI Tech. Rev. 71 83 (2010)
Hashimoto et al. PSSA **209** 501 (2012)

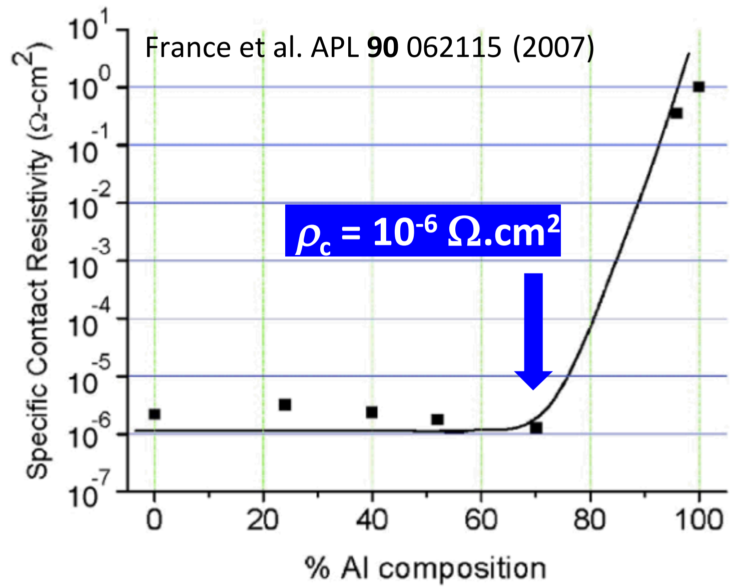
- Sandia AlGaN channel quality tracks with SOA
- ***R_{sh}* < 2500 Ω/sqr. achievable with threading dislocation reduction**

A. Armstrong et al., ICMAT 2015

Challenge: Ohmic Contacts

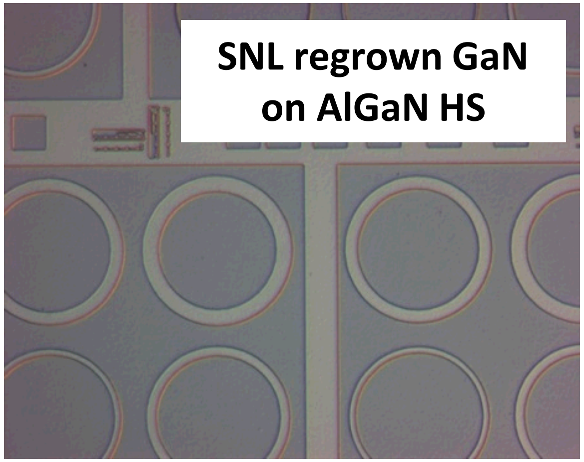
ρ_c increases rapidly with alloying





- Planar/surface Ohmic contacts are a significant challenge
- **Re-grown AlGaN contacts are likely required**

A. Armstrong et al., ICMAT 2015

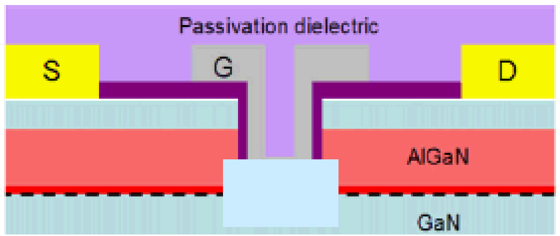


A. Allerman / E. Douglas

Challenge: Normally-Off Devices

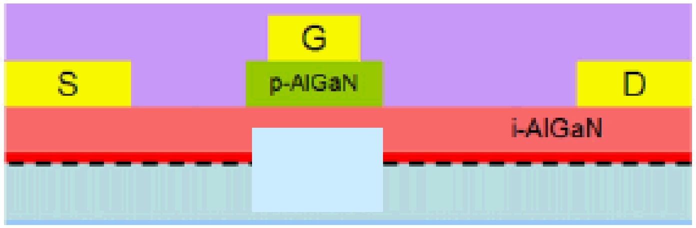
Su et al., SST **28** 074012 (2013)

Recessed Gate HEMT



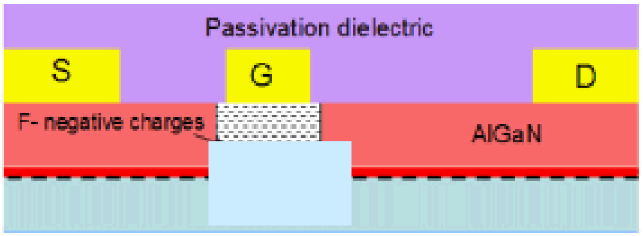
- Gate etch damages channel quality
- Gate leakage concerns
- Low yield across wafer

p-type Gate HEMT



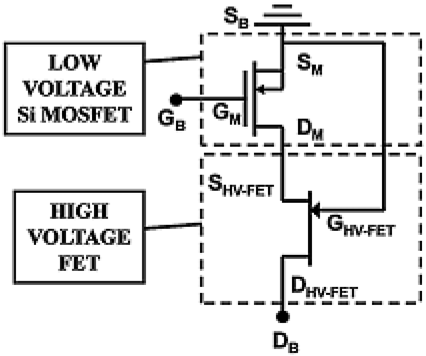
- Highly defective *p*-AlGaN produces dynamic R_{on}
- Mg is undesirable in MOCVD HEMT epi
- Unclear if *p*-type UWBG AlGaN possible

F^--implant HEMT



- F^- implant damages channel quality
- Long-term stability of F^- ions uncertain

Cascode

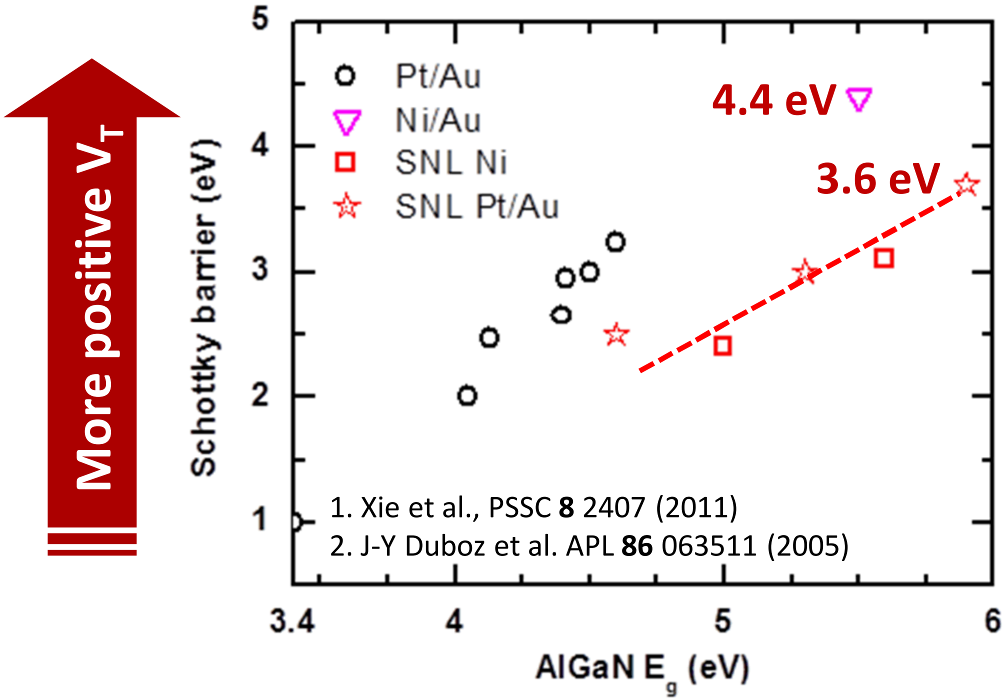


Baliga, SST **28** 074011 (2013)

- Lose thermal margin gains
- Lose switching speeds gains

Strategies for E-mode GaN increase cost and degrade reliability/performance

High Schottky Barriers for E-Mode Operation



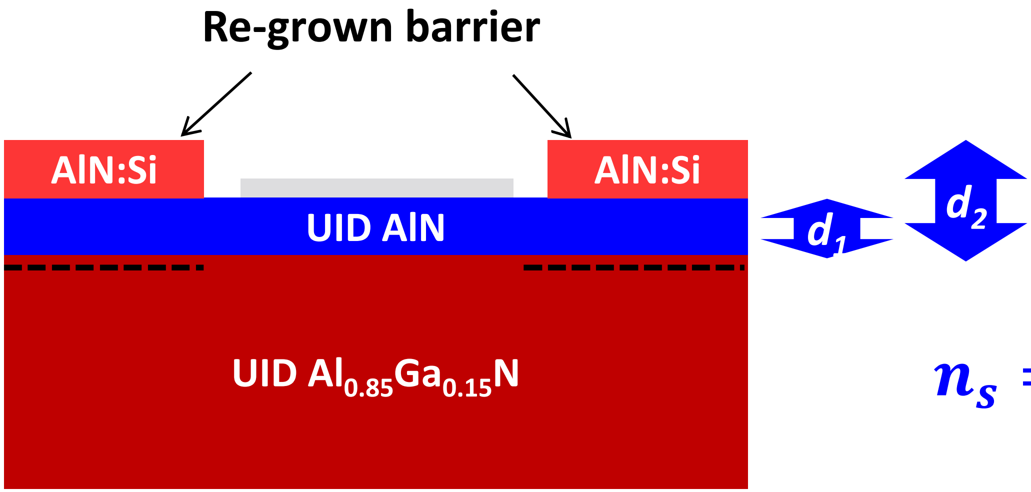
AlGaN Schottky barrier vs. alloying

$$V_{th} = \frac{\phi_B}{q} - \frac{\Delta E_c}{q} - \frac{qN^+d^2}{2\epsilon}$$

- ϕ_B > 4 eV for $Al_{0.8}Ga_{0.2}N$
- Sandia achieved ϕ_B = 3.6 eV for $Al_{0.9}Ga_{0.1}N$
- > +3 V gain in V_T for $AlN/Al_{0.85}Ga_{0.15}N$ compared to GaN HEMTs

A. Armstrong et al., ICMAT 2015

Combine High Schottky Barrier with Regrown Access Region



$$V_T = \frac{\phi_B}{q} - \frac{\Delta E_C}{q} - \frac{qN^+ d_1^2}{2\epsilon}$$

$$n_s = \frac{N^+(d_2^2 - d_1^2)}{2d_2} + \frac{\Delta E_C \epsilon}{d_2} - \frac{\phi_S \epsilon}{d_2}$$

- Non-planar device decouples V_T and $R_{on,sp}$
- Re-grown barrier instead of recess etch to preserve channel quality
- Large AlGaN ϕ_B is critical to preserve sufficient barrier thickness

A. Armstrong et al., ICMAT 2015

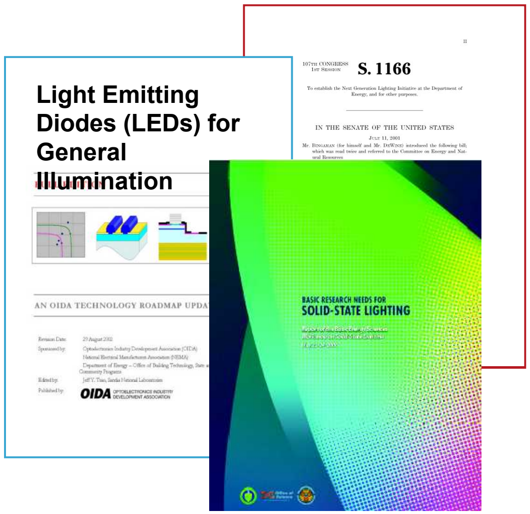
Questions?

Contact information:
Bob Kaplar
Sandia National Labs
505-844-8285
rjkapla@sandia.gov

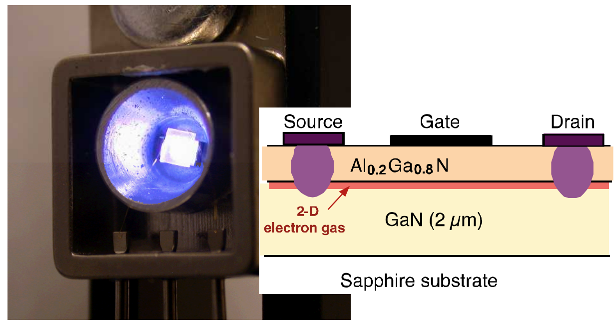
Backups

This Project Builds on 15 Years of Forefront Wide-Bandgap Research at Sandia

1999-2006: Comprehensive US Technology Roadmaps

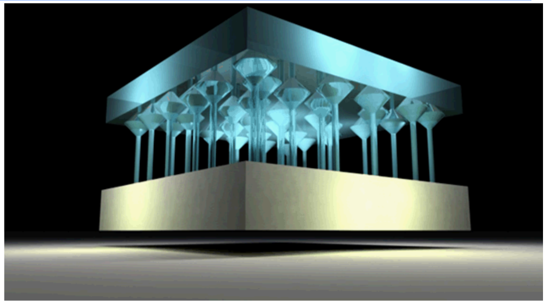


2003-2007: high power amplifiers, UV emitters



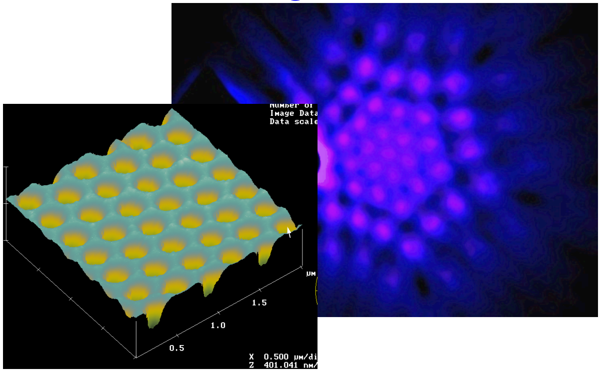
2009-2014: DOE EFRC for SSL Science

SSLS EFRC
SOLID-STATE LIGHTING SCIENCE ENERGY FRONTIER RESEARCH CENTER



2006-2008: DOE /EERE National Center for SSL

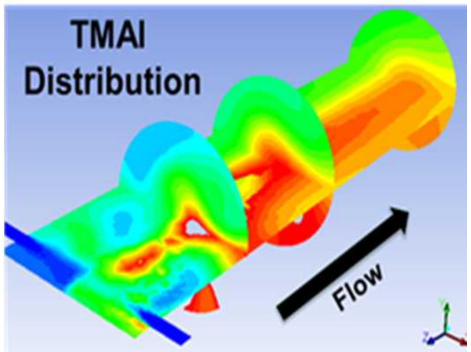
2000-2004: Grand Challenge LDRD

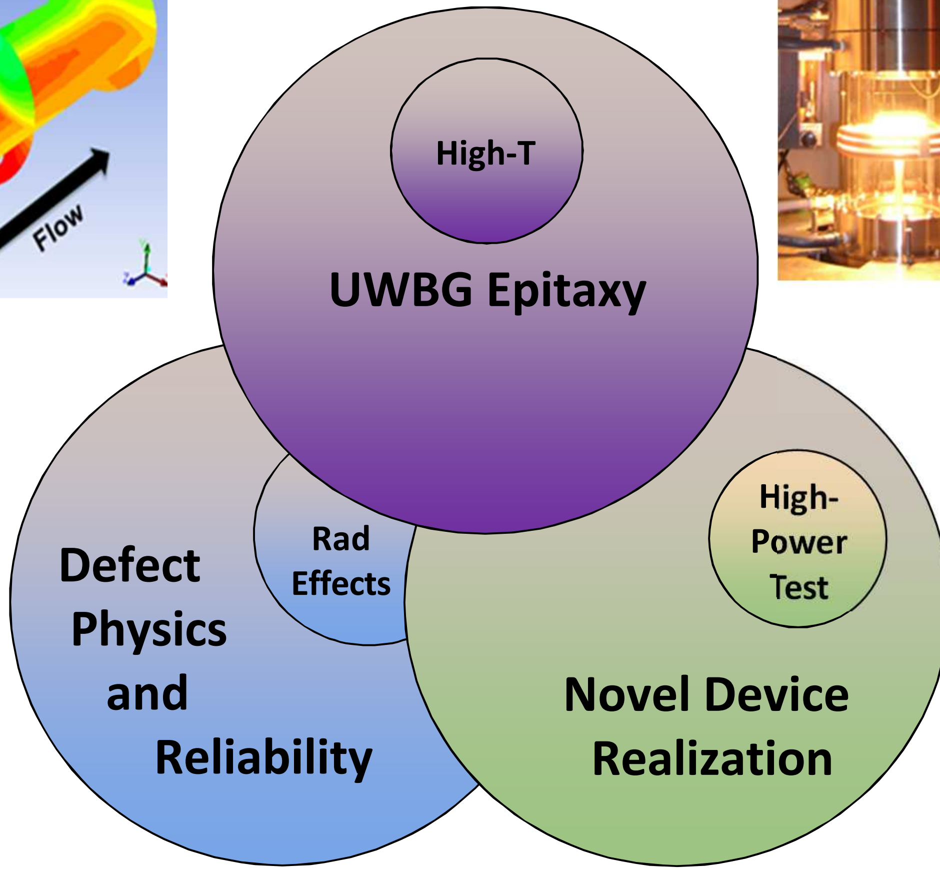


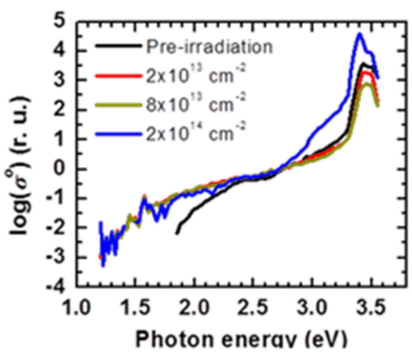
2003-2012: DOE-Funded Collaborations with industry

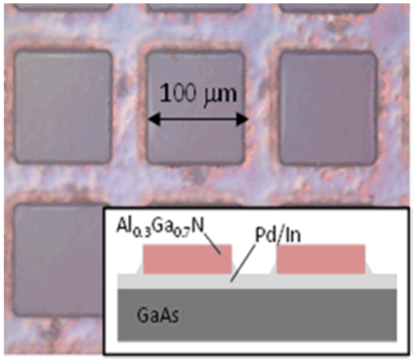
R&D 100

UWBG Project Team Structure









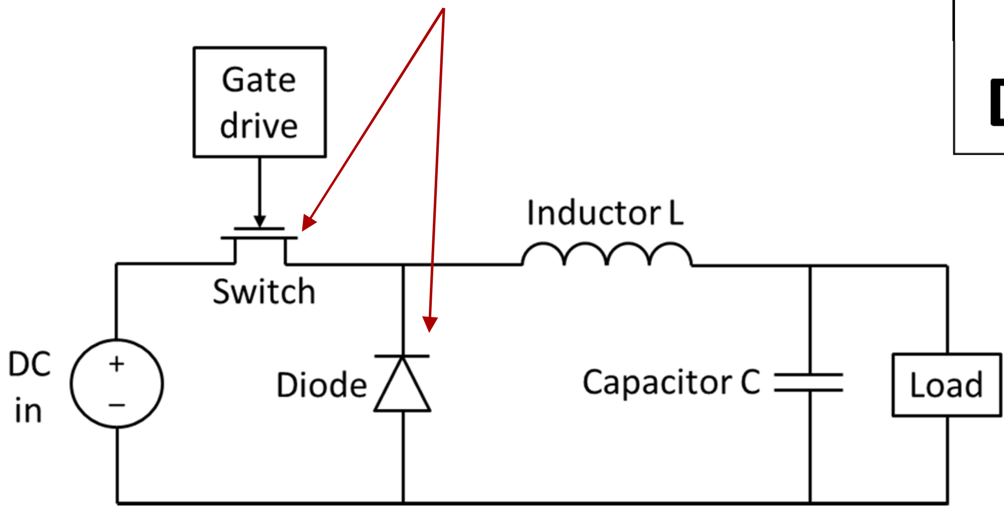
Higher Switching Frequency Enables Reduction in Passive Element Volume and Weight

ULTRAWIDE BANDGAP POWER ELECTRONICS

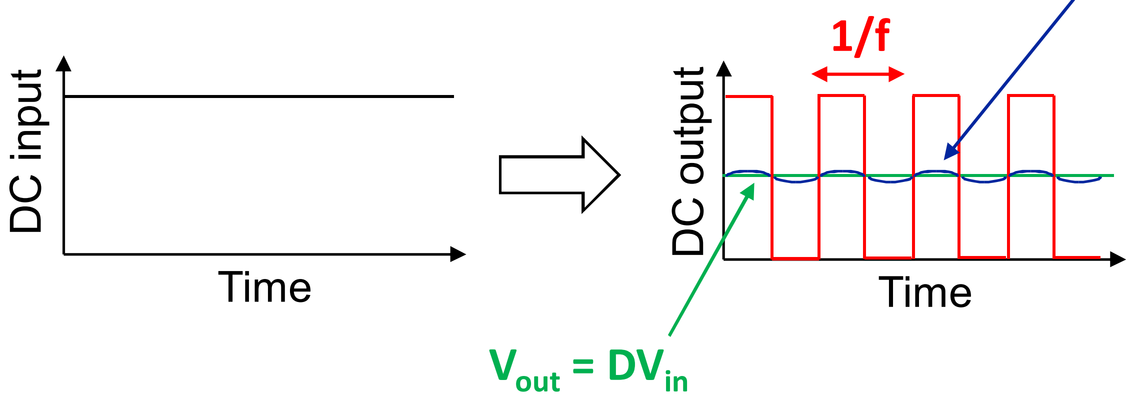
Sandia National Laboratories

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

Power semiconductor devices

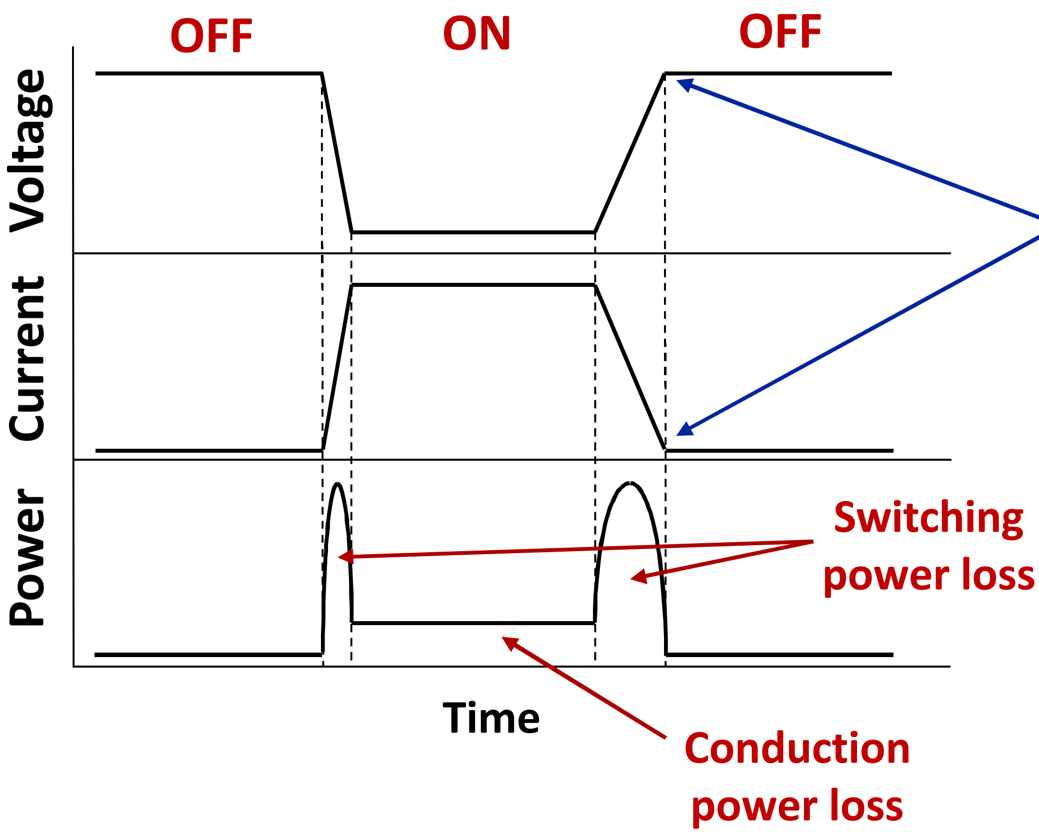


$$\frac{V_{ripple}}{V_{out}} = \frac{1 - D}{8LCf^2}$$

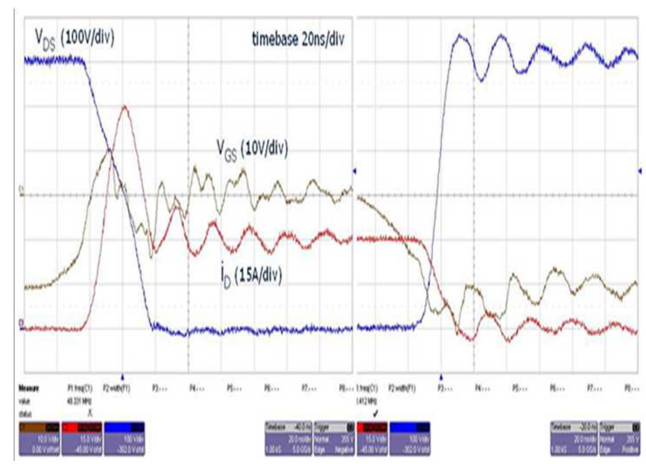


Increasing f allows one to reduce L and C while keeping the ripple constant

Heat Generation from Semiconductor Conduction and Switching Losses



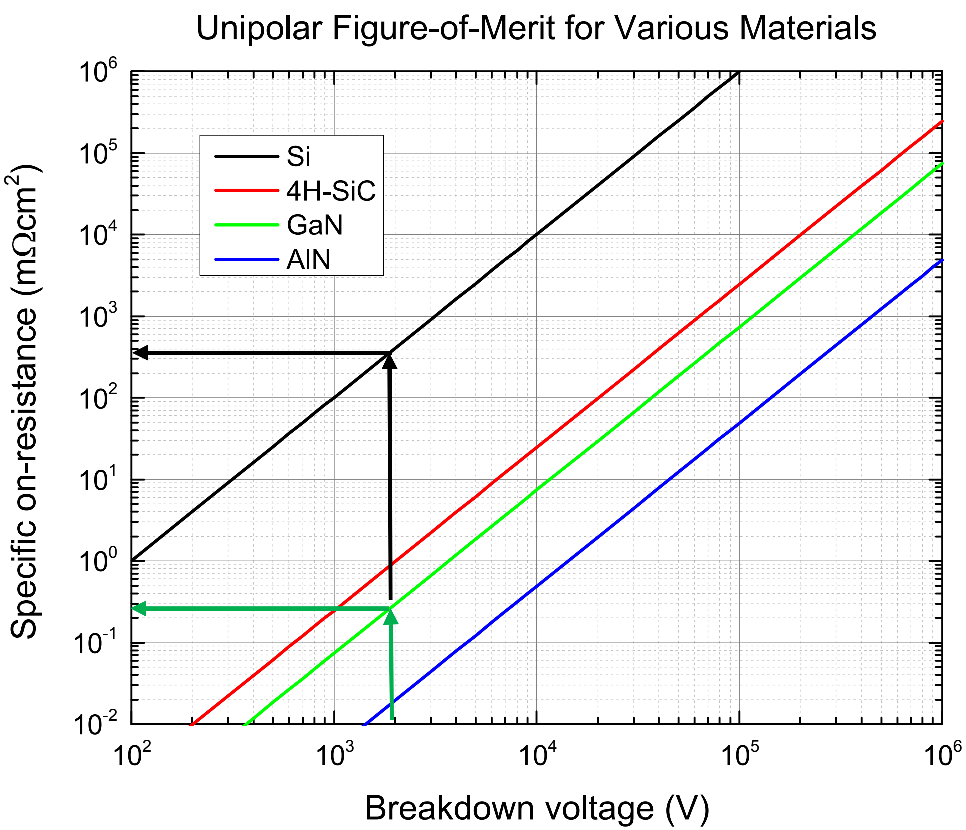
A real circuit will have voltage and current overshoot and oscillations that must be minimized



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

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

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



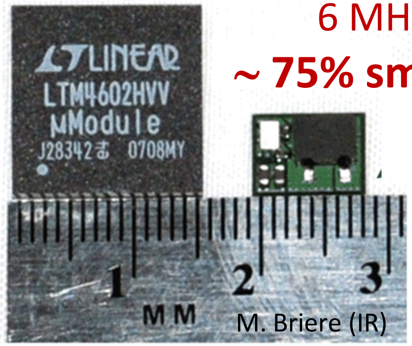
The scaling that results from the properties of WBG and UWBG materials can be utilized to optimize for switching frequency, conduction loss, and switching loss

- **For equivalent breakdown voltage, get lower $R_{on}A$ for WBG device**
  - **For same R_{on}, 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

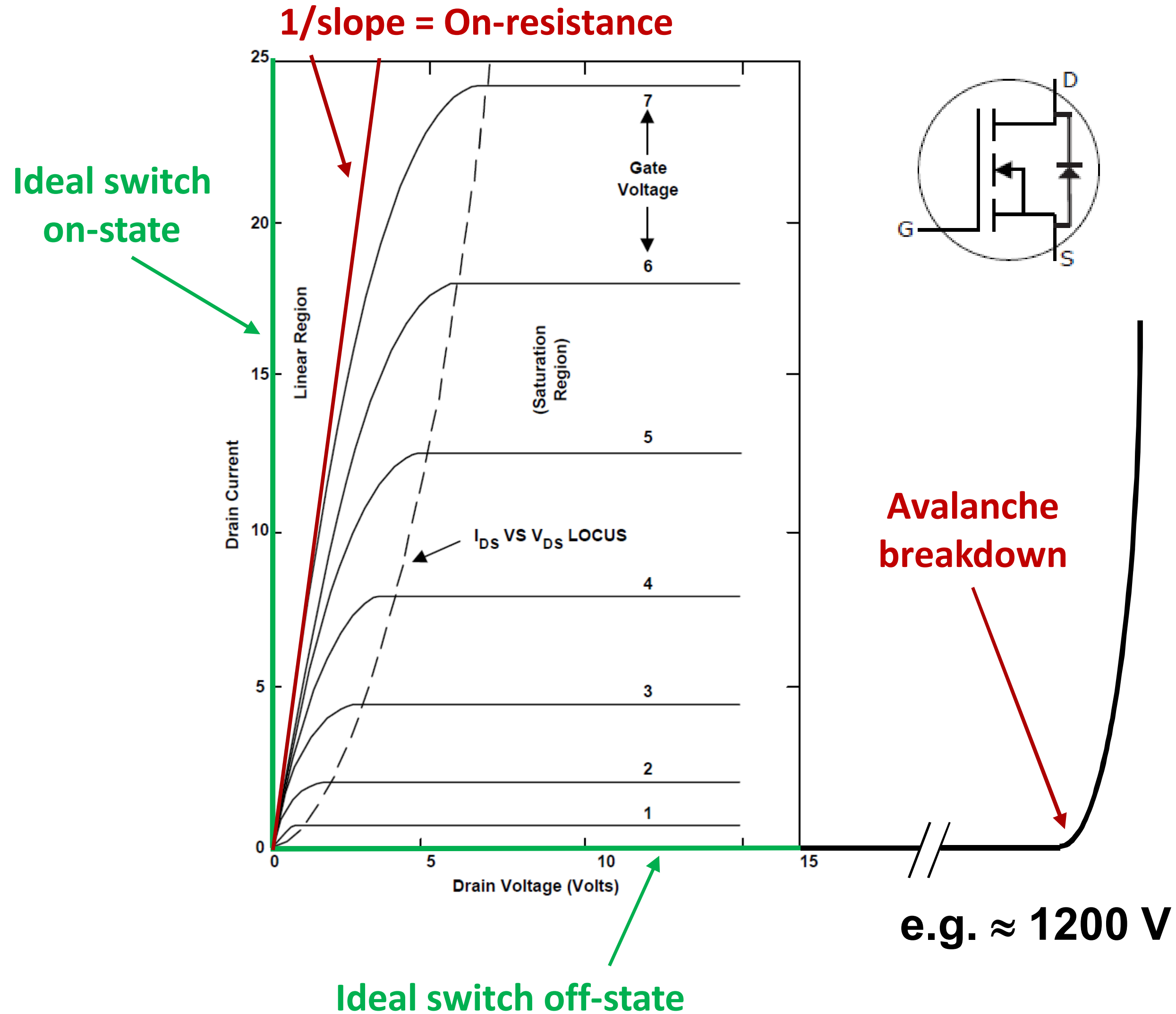
GaN
6x9mm²
6 MHz

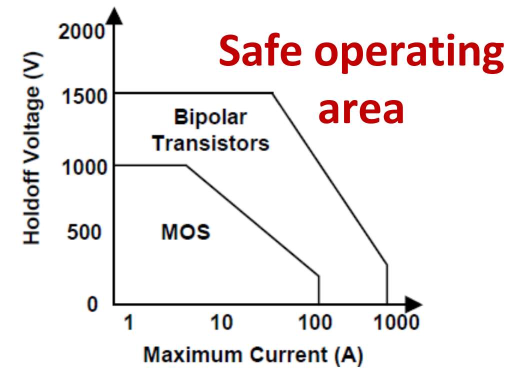
~ 75% smaller

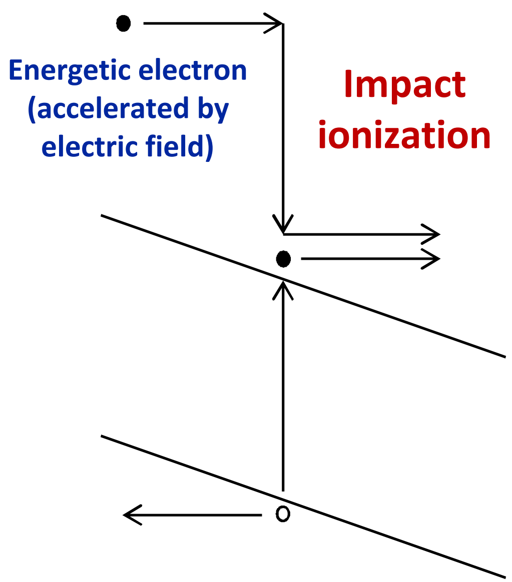


1.2 kV, 12 A switch

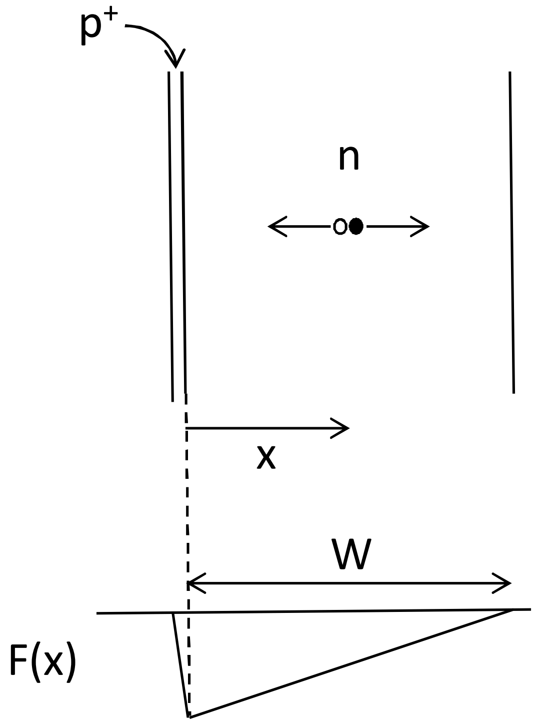
Semiconductor Devices Are *NOT* Ideal Switches







Impact Ionization in a Depletion Region



Impact ionization coefficient for electrons, holes = α_n, α_p = # of ehps generated per cm by an incident hot electron, hole; may be defined in terms of generation rate: $G_{ii} = \alpha_n J_n + \alpha_p J_p$

Suppose that an electron-hole pair is generated at position x. Then the number of ehps N(x) generated at position x is (1):

$$N(x) = 1 + \int_0^x \alpha_p N(x')dx' + \int_x^W \alpha_n N(x')dx'$$

This can be differentiated to give:

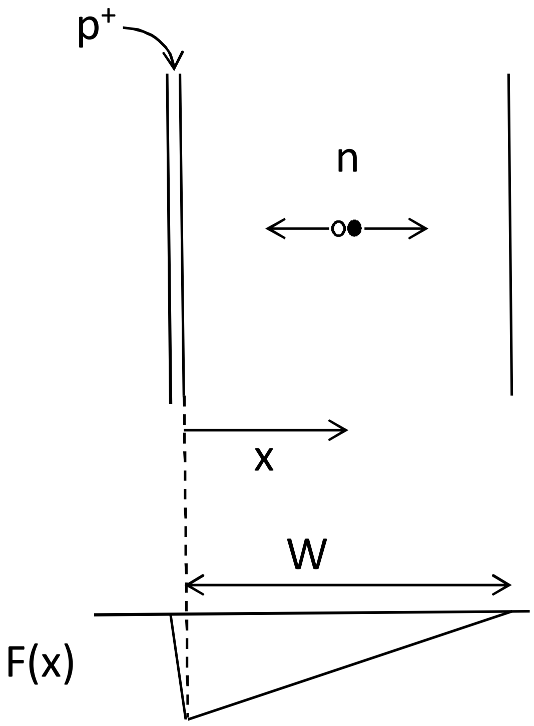
$$\frac{dN}{dx} = (\alpha_p - \alpha_n)N(x)$$

The solution of the differential equation is:

$$N(x) = N(0)exp\left[\int_0^x (\alpha_p - \alpha_n)dx'\right]$$

(1) R. J. McIntyre, "Multiplication Noise in Uniform Avalanche Diodes," IEEE Trans. Elec. Dev. **13(1)**, 164 (1966).

Criterion for Avalanche Breakdown



The equations may be combined to give (after some algebra):

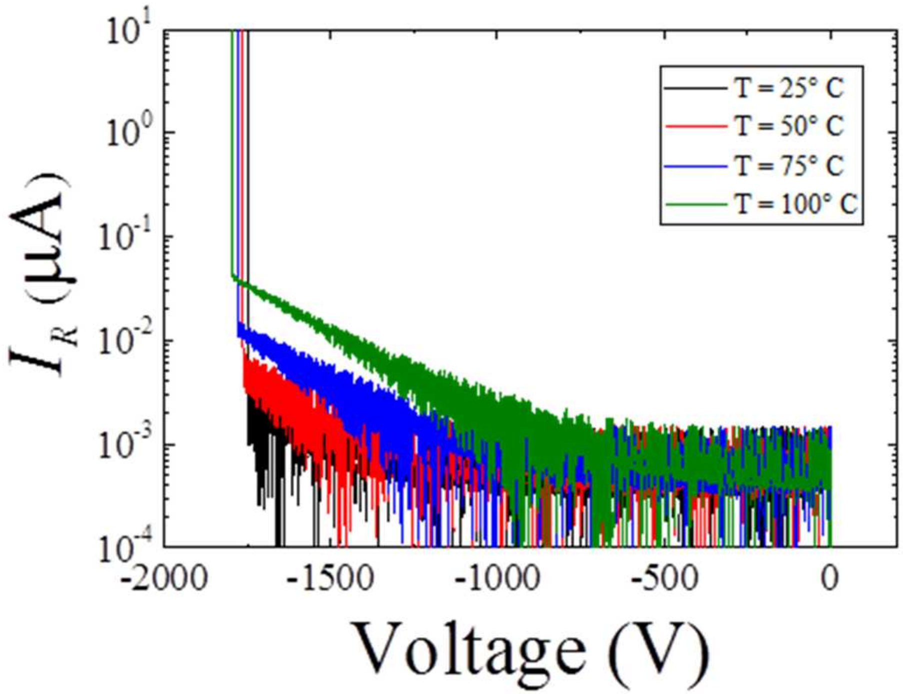
$$N(x) = \frac{exp\left[\int_0^x (\alpha_p - \alpha_n)dx'\right]}{1 - \int_0^W \alpha_n exp\left[\int_0^x (\alpha_p - \alpha_n)dx'\right]dx}$$

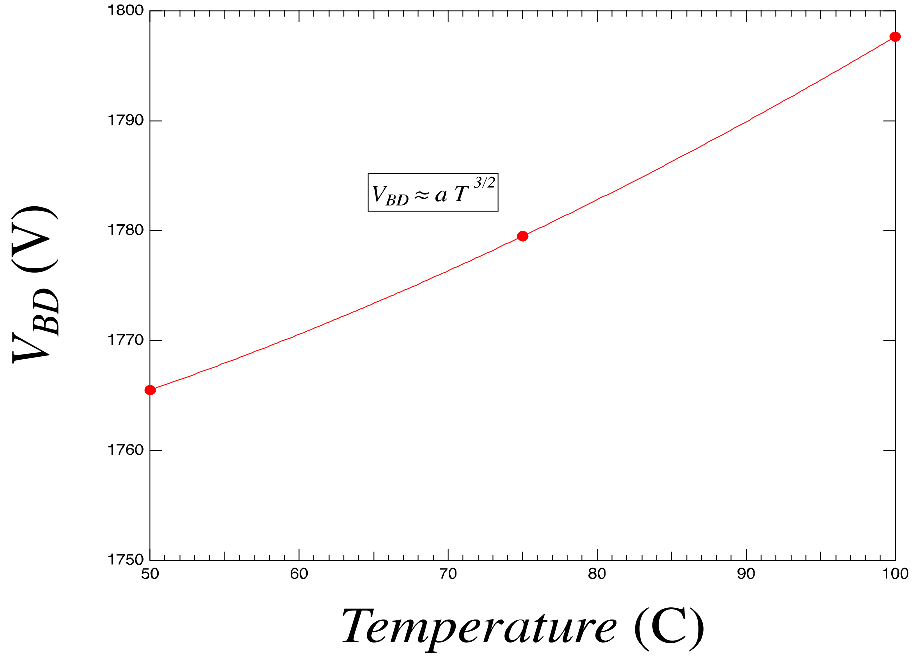
Avalanche breakdown occurs when the number of generated ehps tends to infinity, i.e. when the denominator goes to zero:

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

Since a_n and a_p are such strong functions of electric field, in practice this always occurs near the location of peak field, and the majority of the contribution to the integral is from a small volume near this point (i.e. at the junction).

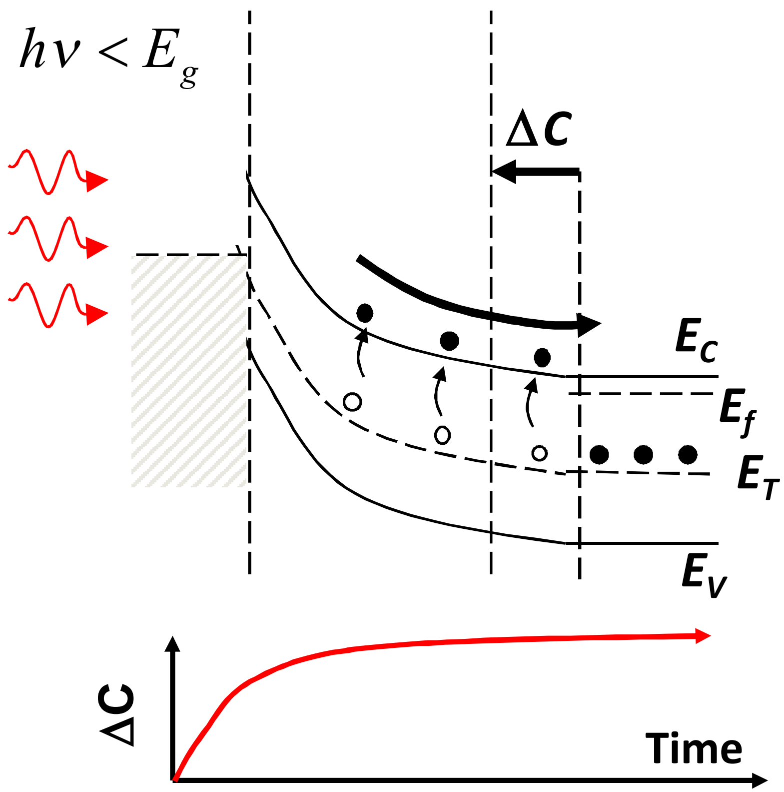
Reverse Breakdown vs. Temperature

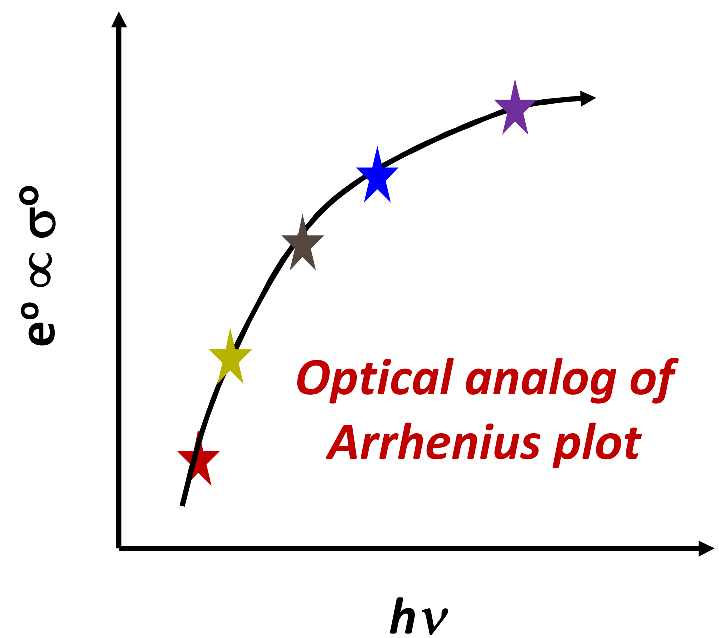




- **Increasing temperature leads to increased leakage current (possibly generation current)**
- **V_B vs T exhibits $T^{3/2}$ dependence, consistent with avalanche processes impeded by phonon scattering**

Deep Level Optical Spectroscopy





DLOS is able to probe the entire bandgap of GaN

Electrical measurement **of** ***optical absorption*** **by deep level defects**

- **Photocapacitance technique**
- **Sub-bandgap optical stimulation to photoionize defect levels**
- **Determine deep level energy E_o from lineshape of $\sigma^o(h\nu)$**