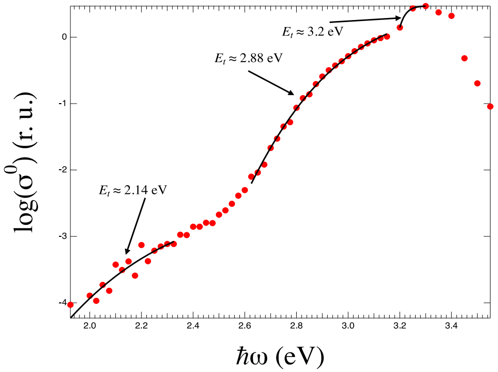
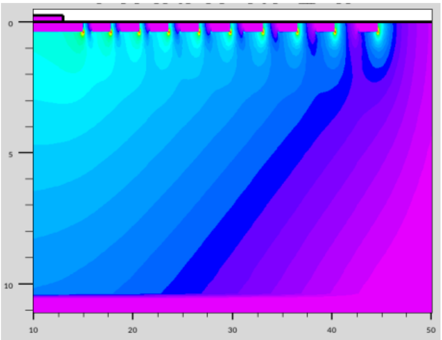
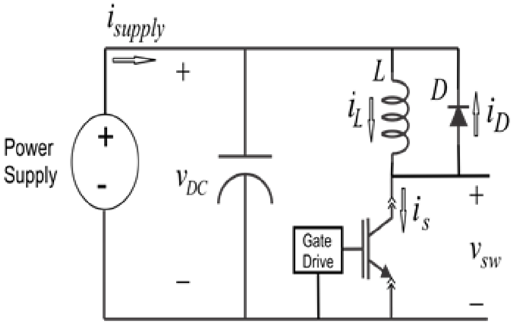
Ultra-Wide-Bandgap Semiconductors for Power Electronics

SAND2015-1674PE







Presented by:

Bob Kaplar

Principal Member of the Technical Staff

Sandia National Laboratories

Presented to:

The Albuquerque IEEE Joint Chapters of AP/MTT/EMC/NPS and PES/PELS Societies

The Canyon Club, Albuquerque, NM

February 25, 2015

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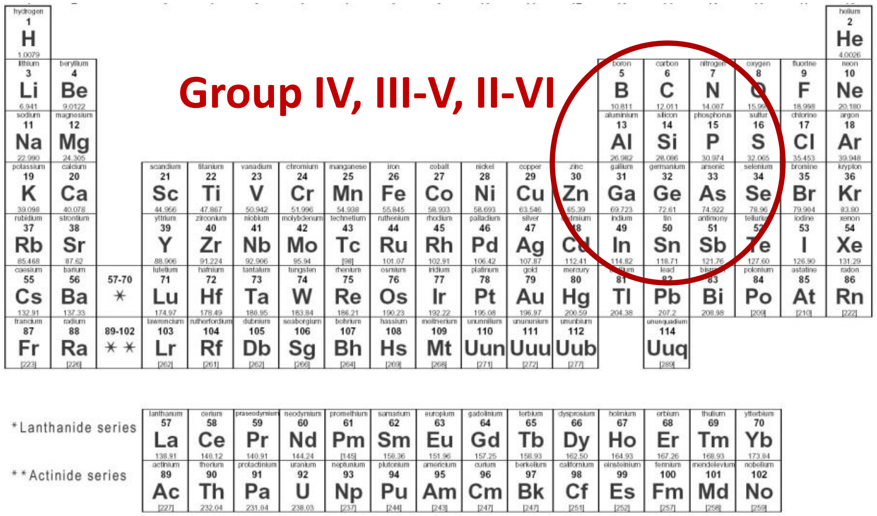
Outline

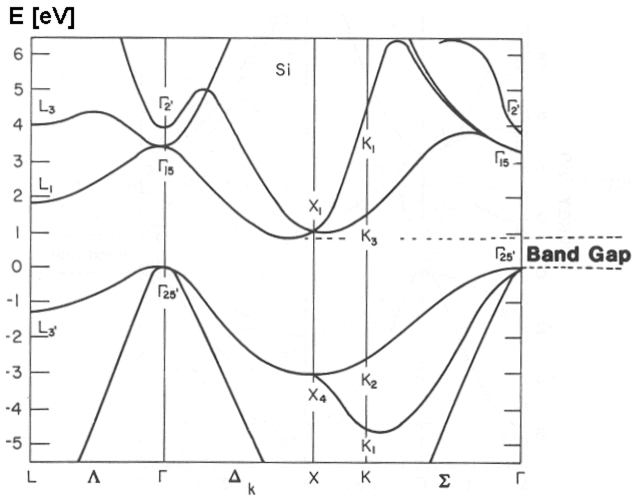
- **First part of the talk:**
  - **Overview of semiconductor physics and power electronics**
  - **Why are wide-bandgap (WBG) and Ultra-Wide-Bandgap (UWBG) semiconductors good for power electronics?**

- **Second part of the talk:**
  - **Overview of Sandia's new Grand Challenge LDRD on Ultra-Wide-Bandgap semiconductors for power electronics**

What are Semiconductors?

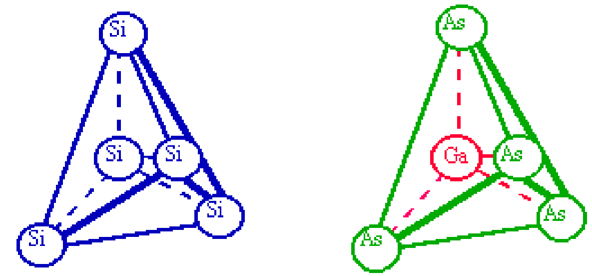


Group IV, III-V, II-VI

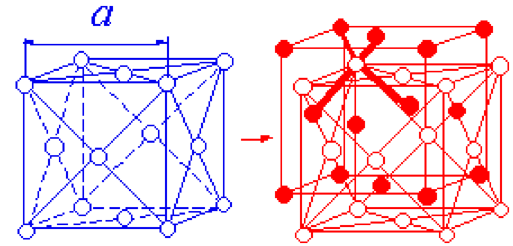


Band-structure of Si

Tetrahedral bonding configuration

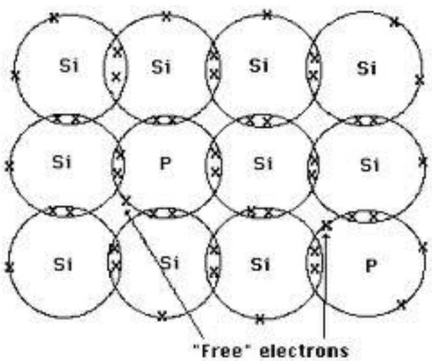


Face Centered Cubic and Diamond Crystal Structure

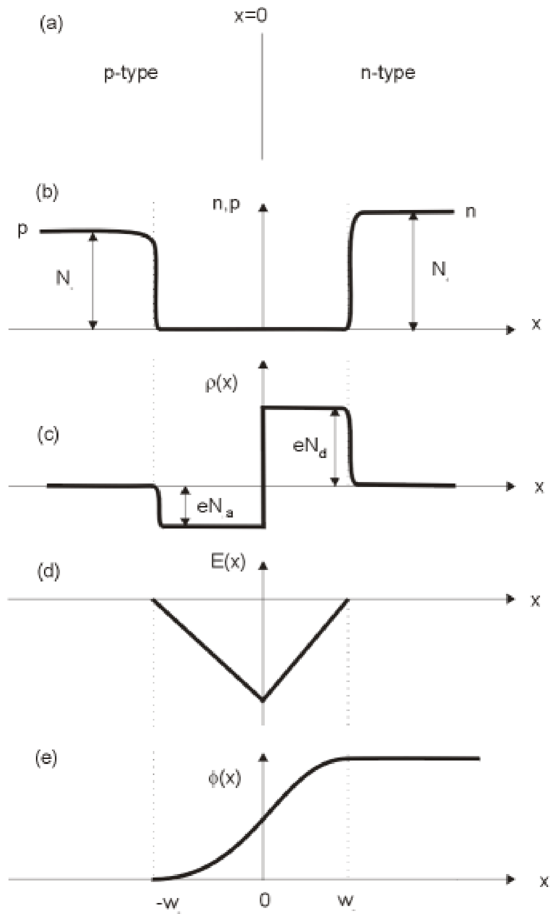


Diamond, Zincblende, or Hexagonal (e.g. 2H, 4H, 6H) crystal structure

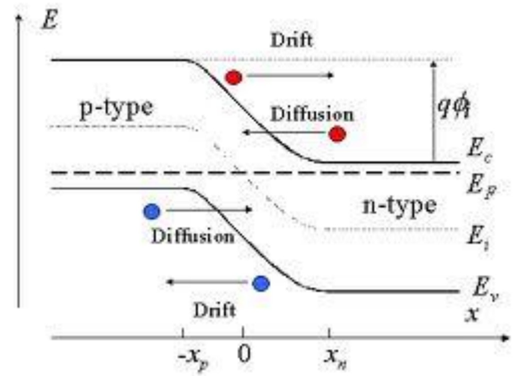
Doping and pn Junctions

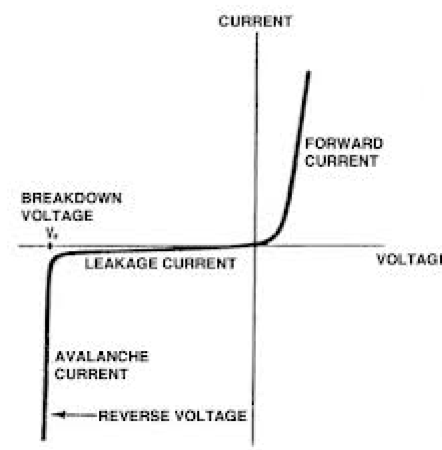


Doping of Si:
Extra electron = n-type
Missing electron = p-type



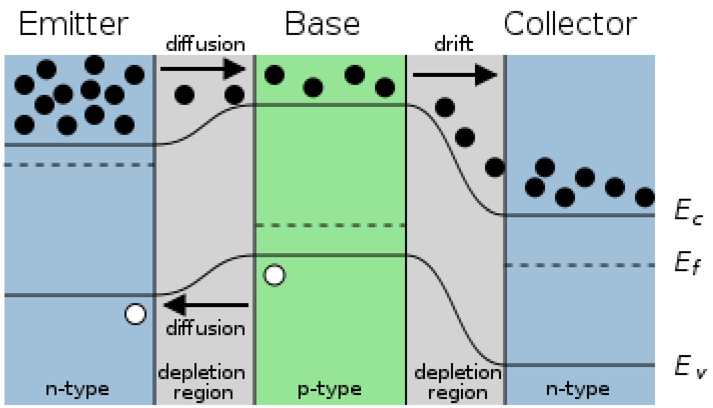
Depletion Layer

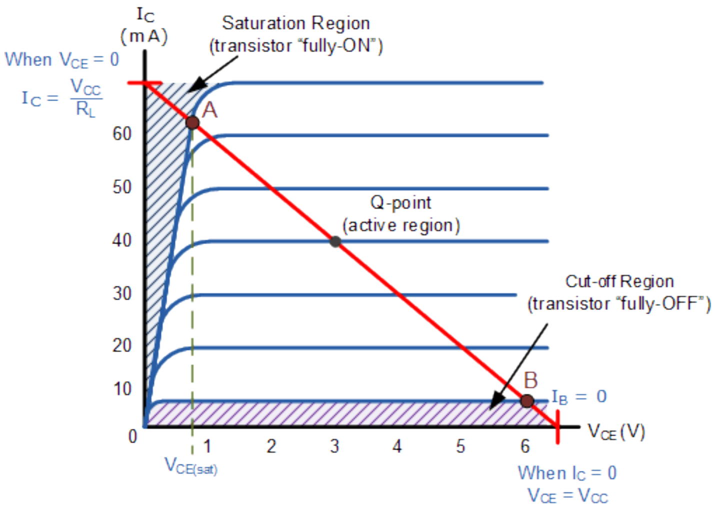




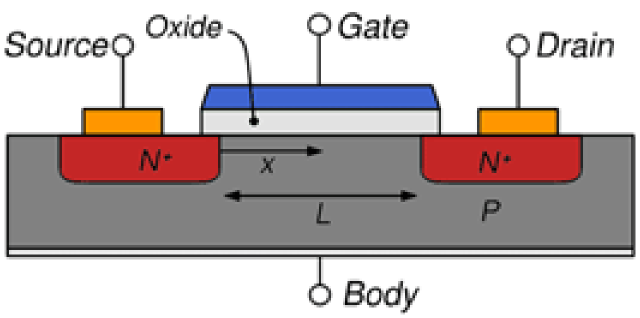
Bipolar and Field-Effect Transistors

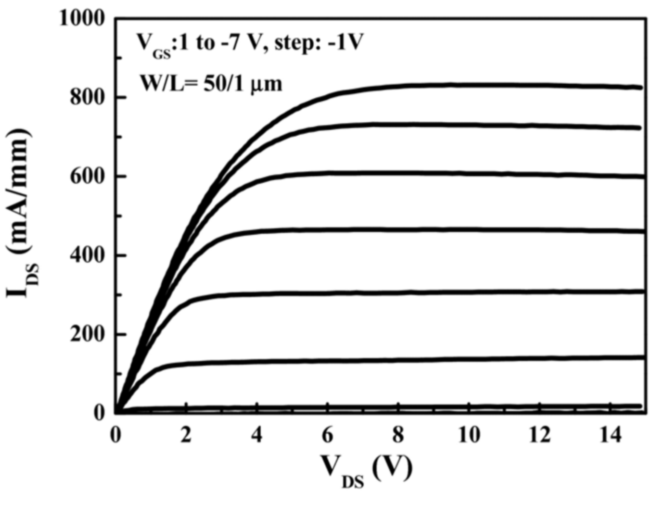
Bipolar





Field-Effect

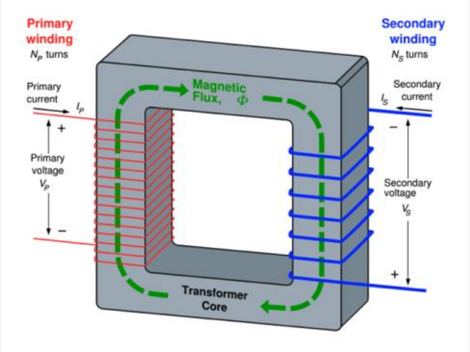




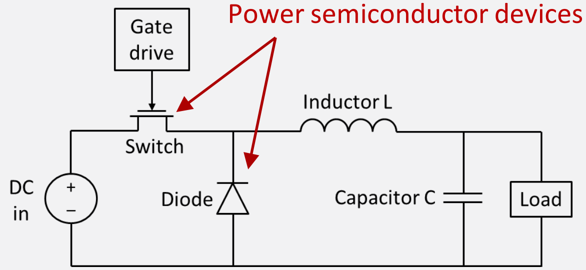
What Are Power Electronics?

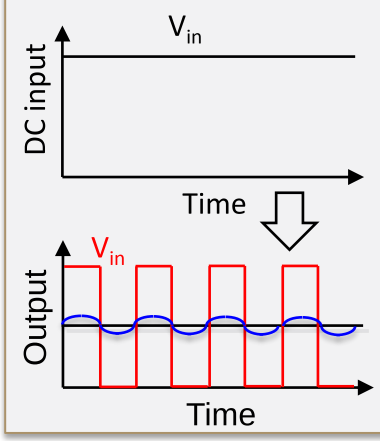
- ***Power electronics***: Application of solid-state electronics for routing, control, and conversion of electrical power

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**

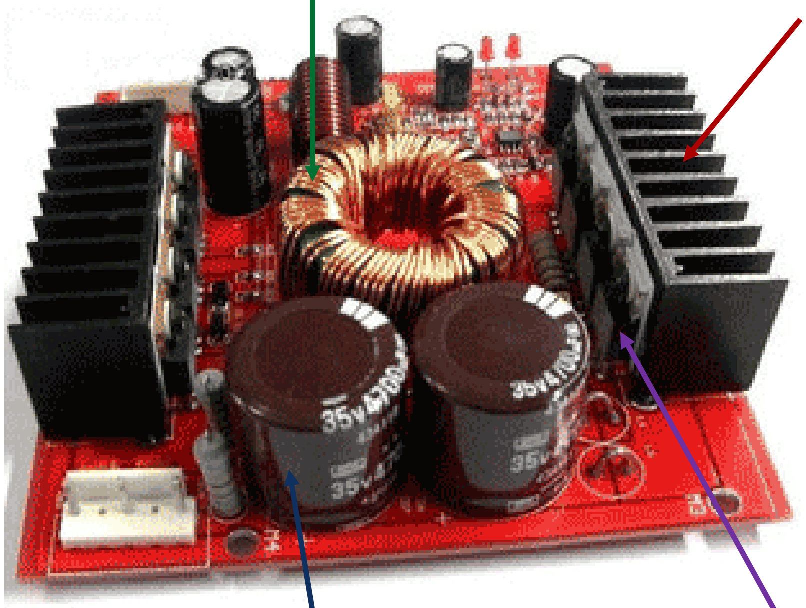
➢ ***Motivation for WBG/UWBG semiconductors***

Power Electronics Volume and Weight Considerations

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

Magnetics

Thermal management

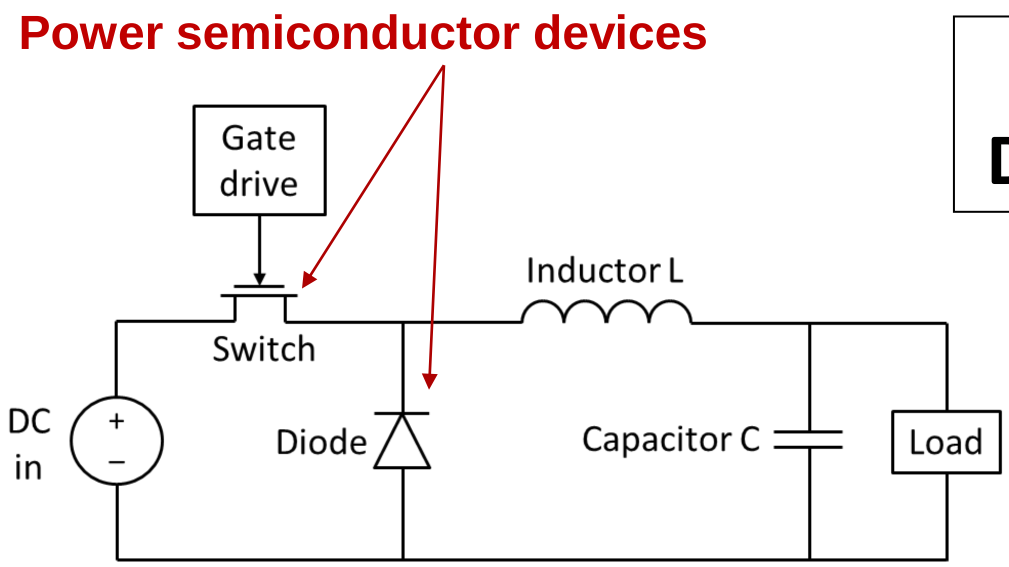


Capacitors

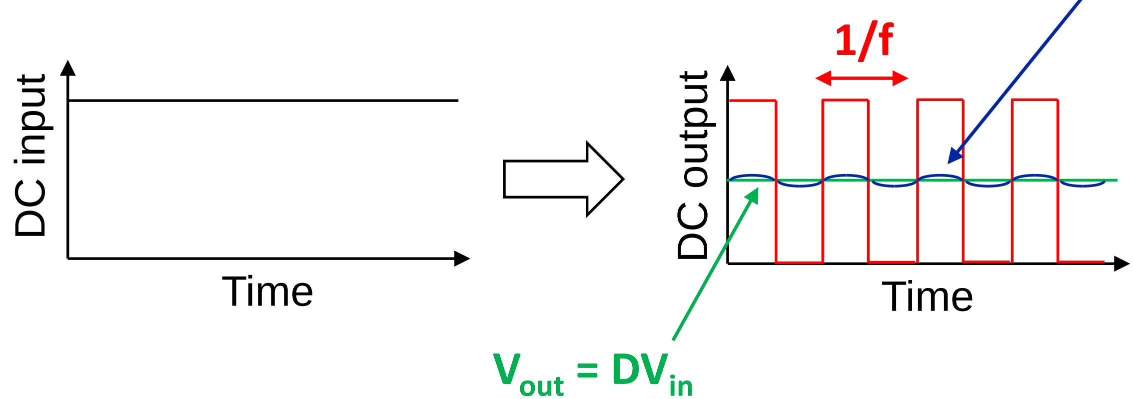
Semiconductor switches

Higher Switching Frequency Enables Reduction in Passive Element Volume and Weight

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



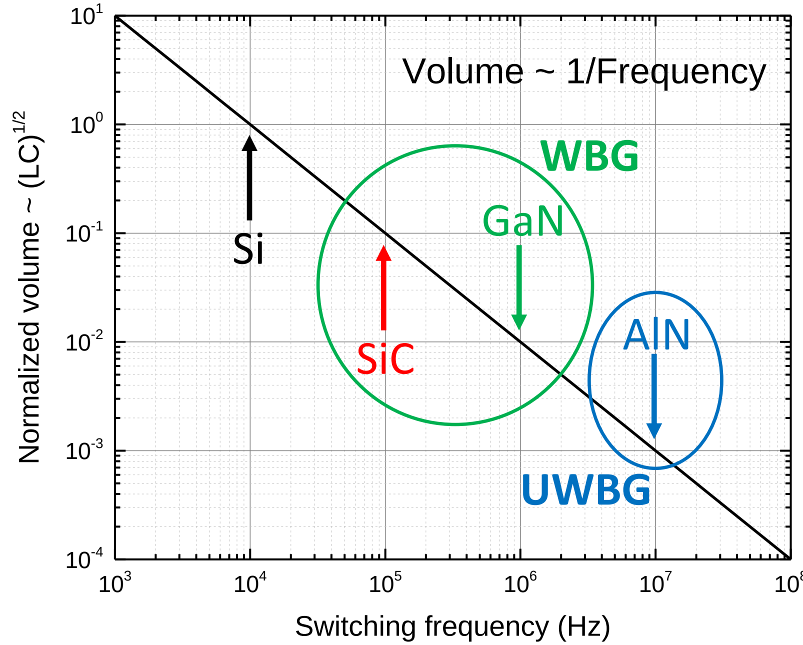
$$\frac{V_{ripple}}{V_{out}} = \frac{1 - D}{8LCf^2}$$



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

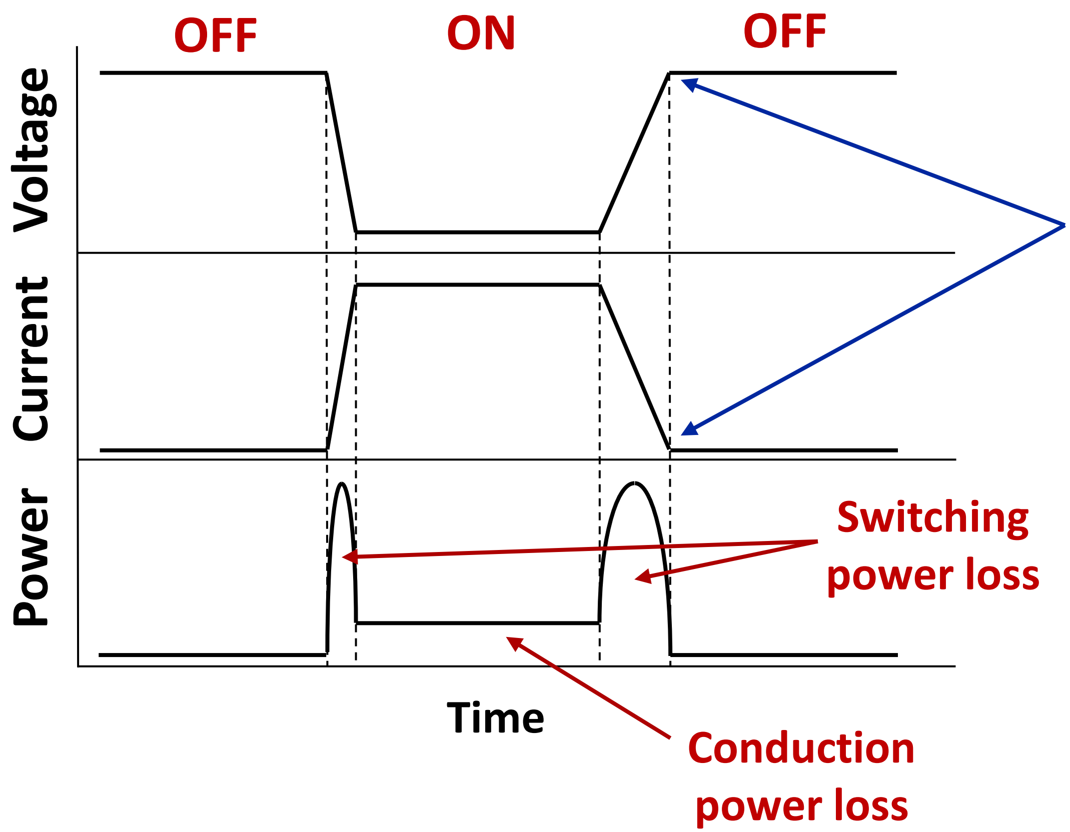
Dramatic Reduction in Power Converter Volume with Increasing Bandgap

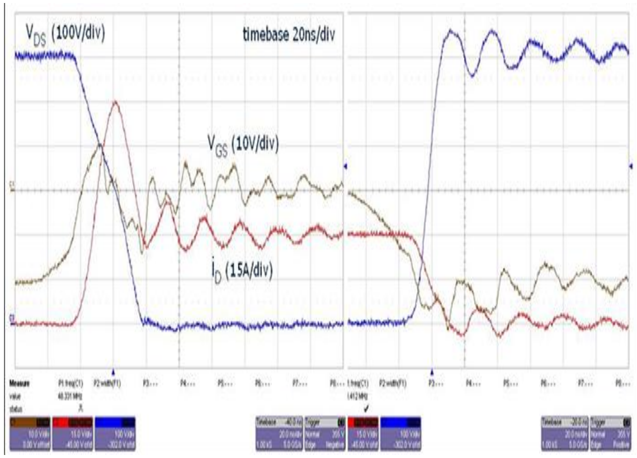
SiC is 10% the volume and weight of Si for equivalent capability (10 kV, 100 A)



UWBG PE may result in *another* order-of-magnitude SWaP improvement compared to WBG PE

Heat Generation from Semiconductor Conduction and Switching Losses

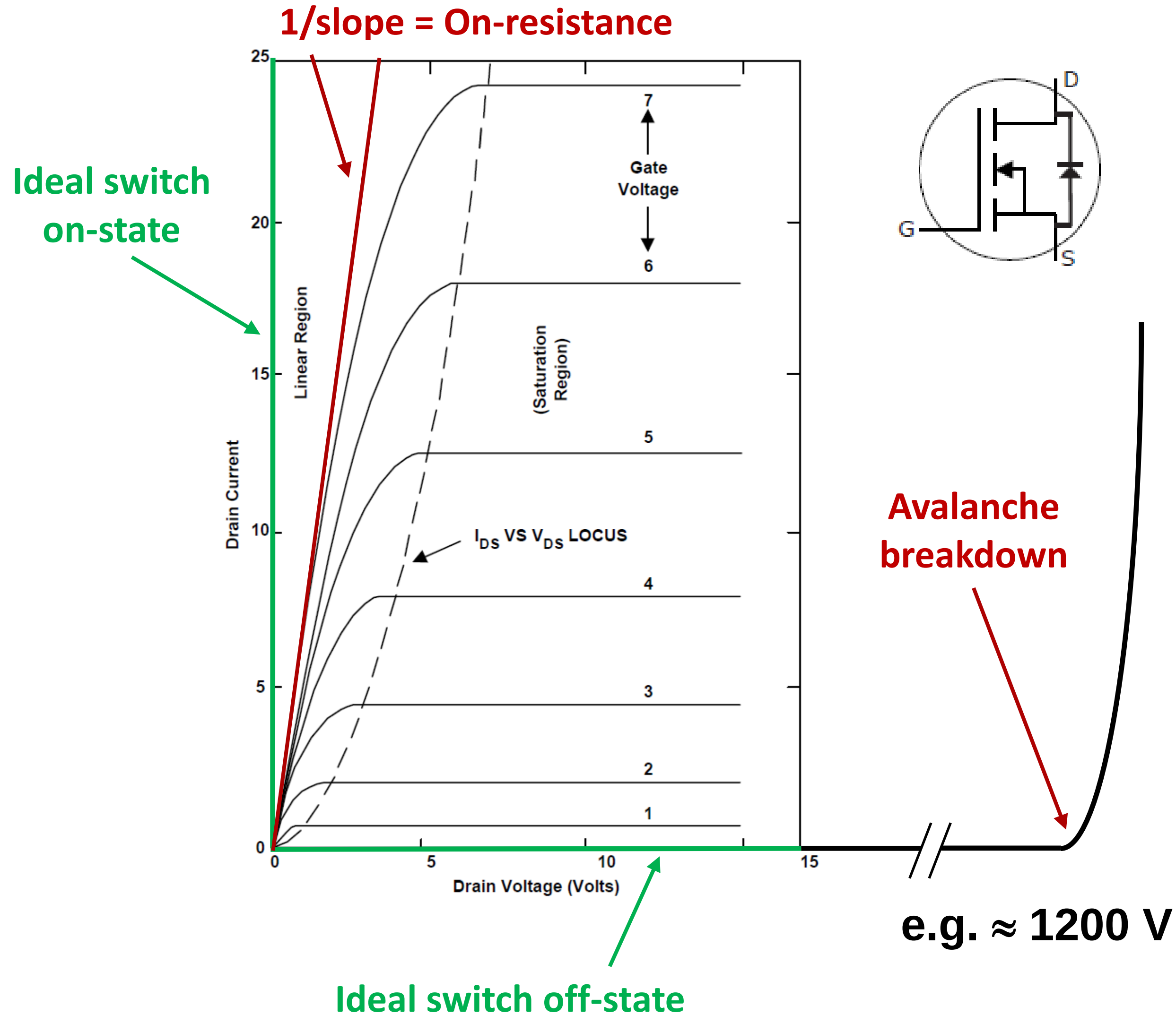


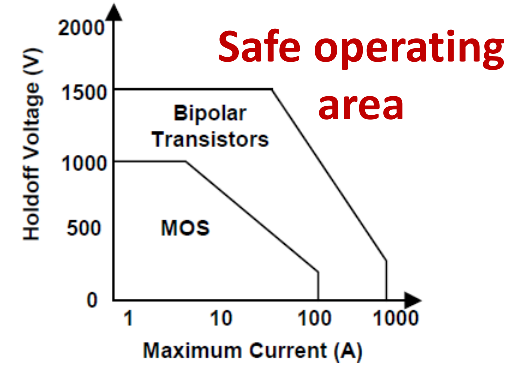


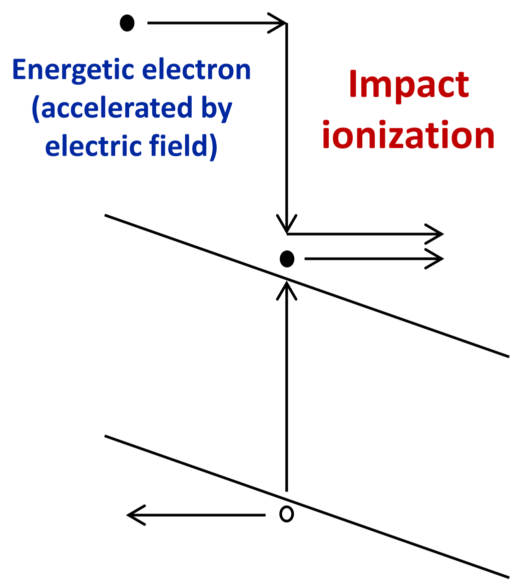
Minimum ON-state loss: *Need low R_{on}*

Minimum switching loss: *Need fast switching transients*

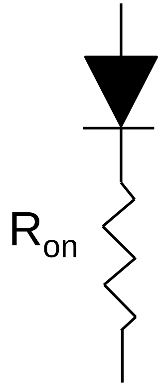
Semiconductor Devices Are *NOT* Ideal Switches

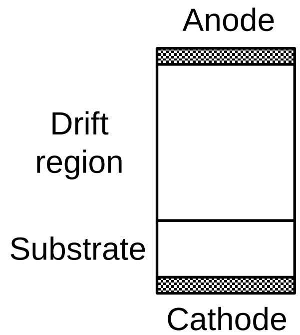


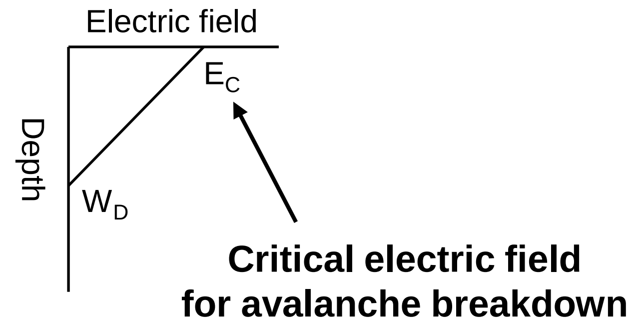




Breakdown Voltage and Figure-of-Merit Are Strong Functions of Critical Electric Field







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

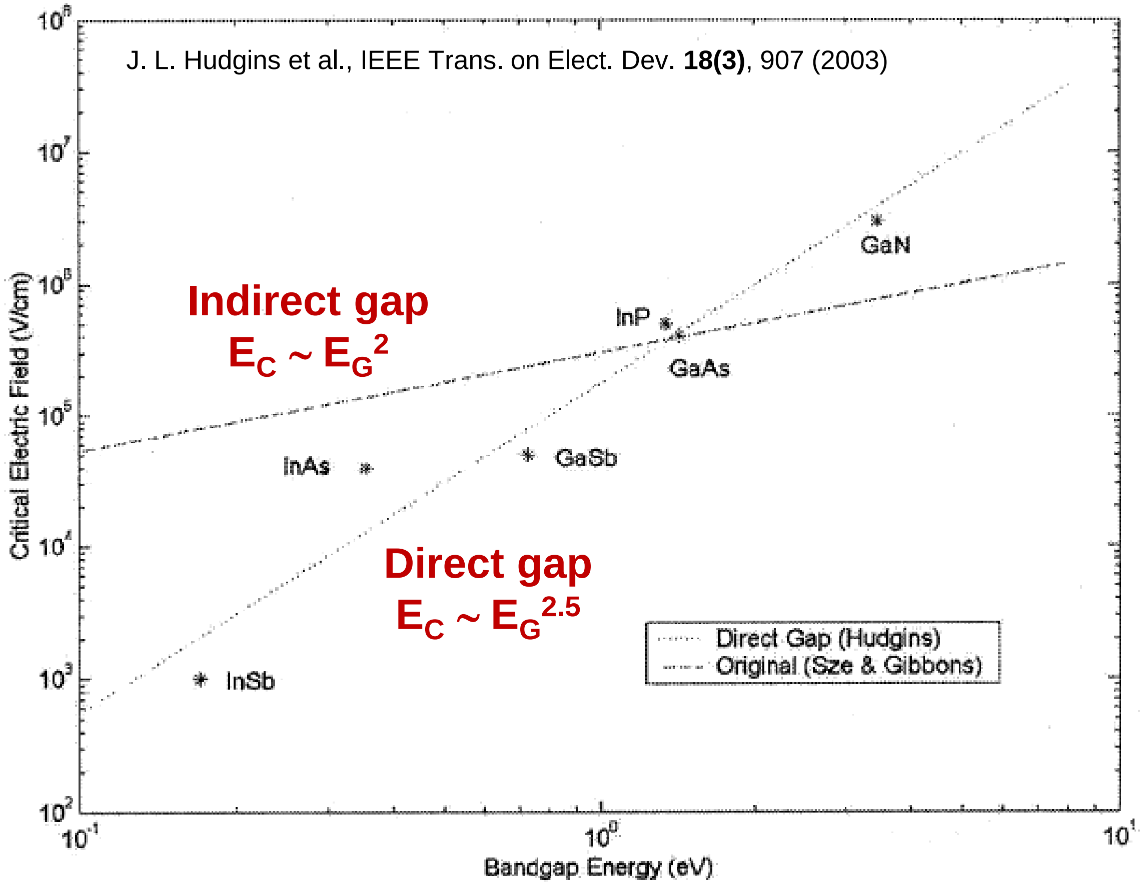
- Combining (1) and (2) gives dependence of V_B on N_D and E_C: $\mathbf{V_B = \varepsilon E_C^2/2qN_D}$

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

Depends on cube of E_C

Depends on square of E_C

The Critical Electric Field is Large for WBGs and Even Larger for UWBGs



$E_G(GaN)/E_G(Si) = 3.4/1.1 = 3.1$

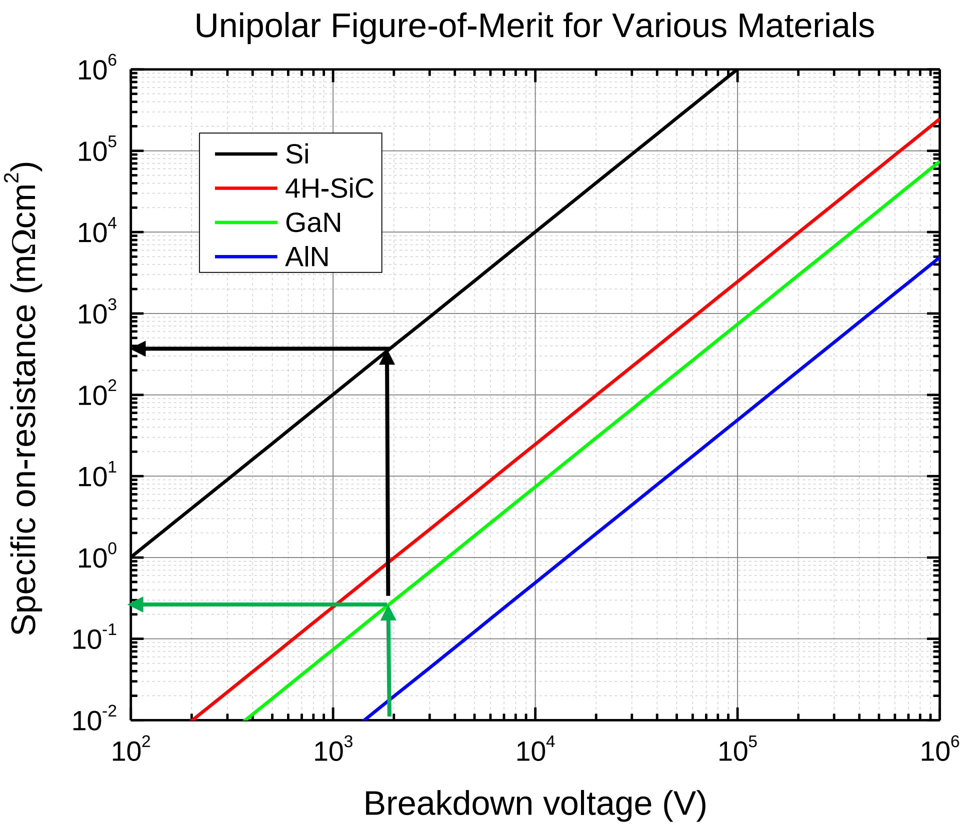
$E_C(GaN)/E_C(Si) \approx 3.1^2 = 9.6$

Unipolar FOM:

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

$FOM(GaN)/FOM(Si) = 9.6^3 \approx 885!$

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



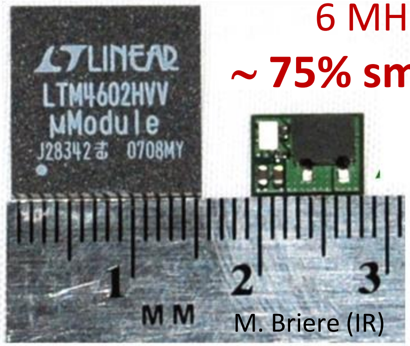
The scaling that results from the properties of WBG and UWBG materials can utilized to optimize for switching frequency, conduction loss, and switching loss

- **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



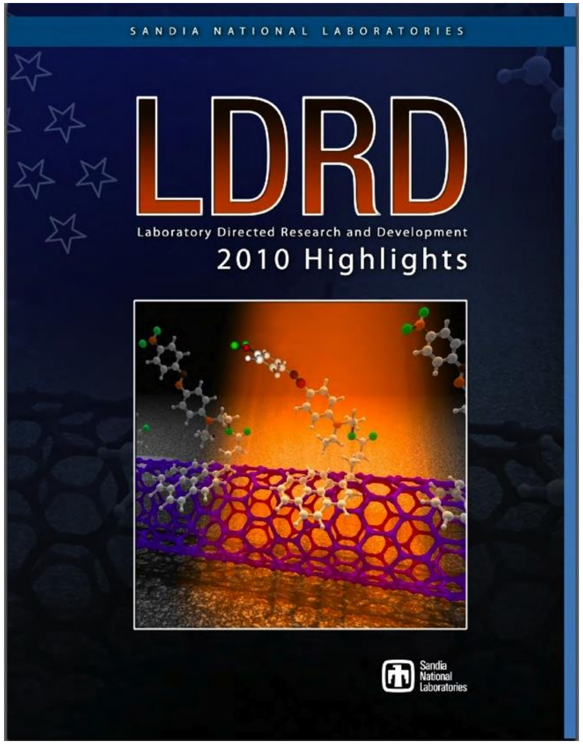
1.2 kV, 12 A switch

Sandia's LDRD Program

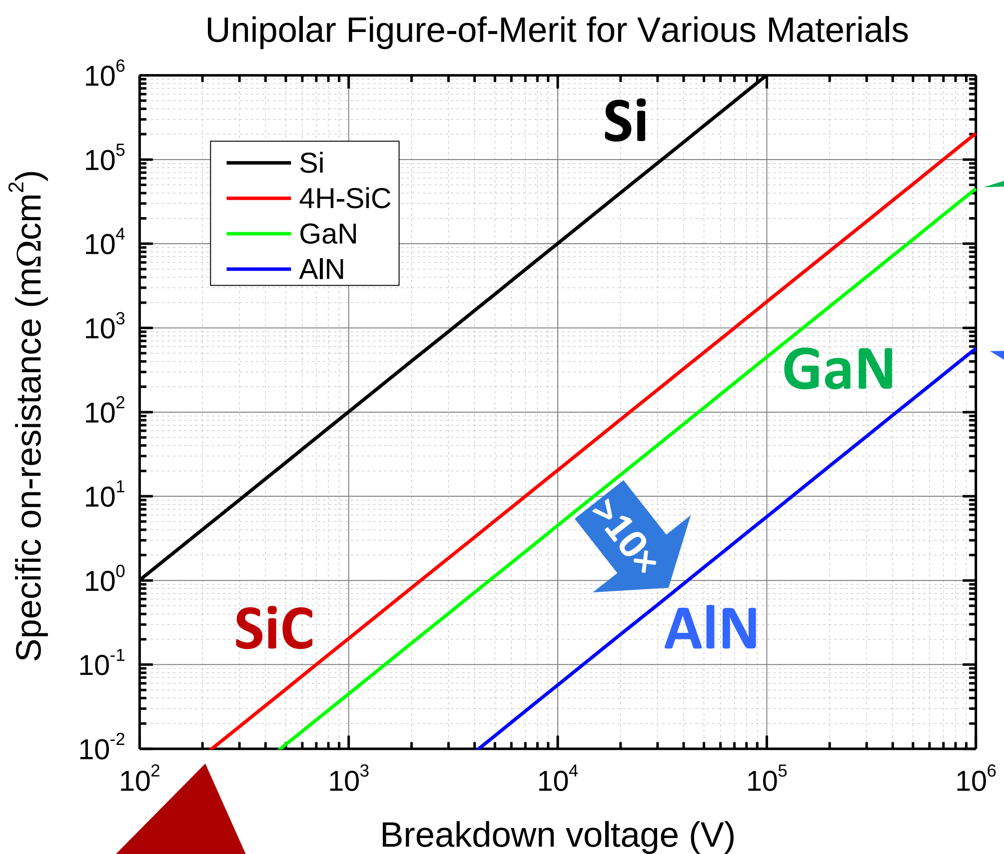
Sandia National Laboratories

LDRD: Laboratory Directed Research & Development

- **Sandia's sole source of discretionary R&D funds**
- **LDRDs "promote creative and innovative R&D that attracts exceptional research talent"**
- **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**



A New Grand Challenge Is Investigating the Next Generation of Materials for Power Electronics



GaN
Lateral devices fairly mature
Vertical devices emerging

UWBG Grand Challenge
Unexplored space
Unprecedented performance

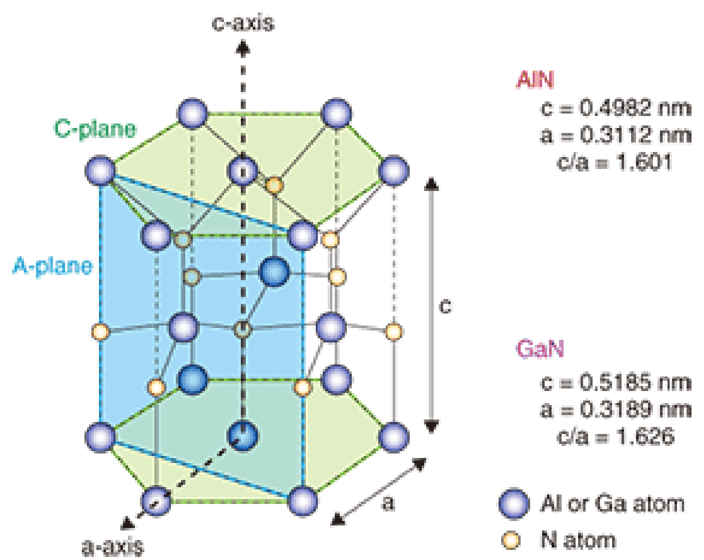
SiC
Many commercial devices available

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

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
Ionization energy (eV/e-h pair)	3.6	4.8	8.7	10.3	18



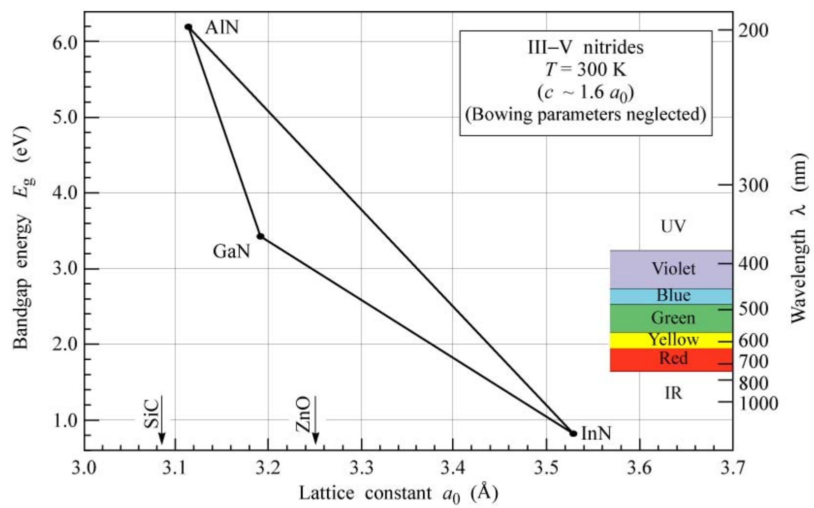


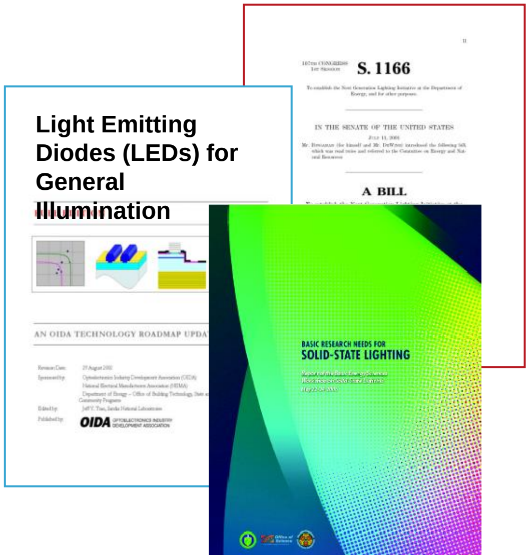
Fig. 12.12. Bandgap energy versus lattice constant of III–V nitride semiconductors at room temperature.

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

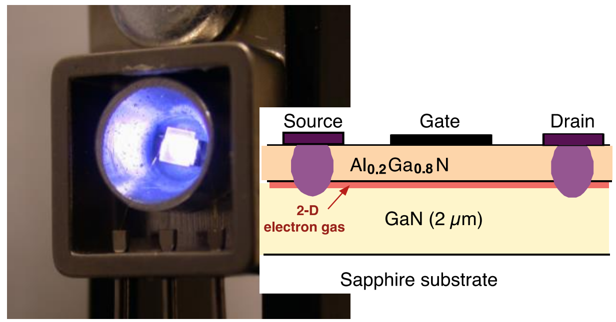
This Project Builds on 15 Years of Forefront Wide-Bandgap Research at Sandia

Sandia National Laboratories

1999-2006: Comprehensive US Technology Roadmaps

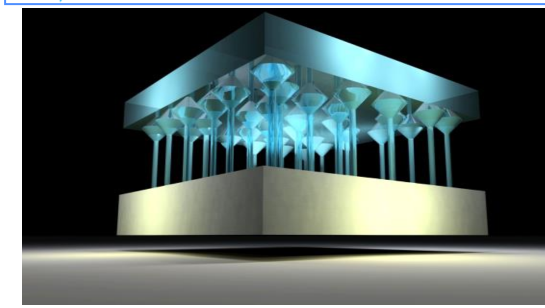


2003-2007: high power amplifiers, UV emitters



2009-2014: DOE EFRC for SSL Science

SSLS EFRC
SOLID-STATE LIGHTING SCIENCE ENERGY FRONTIER RESEARCH CENTER

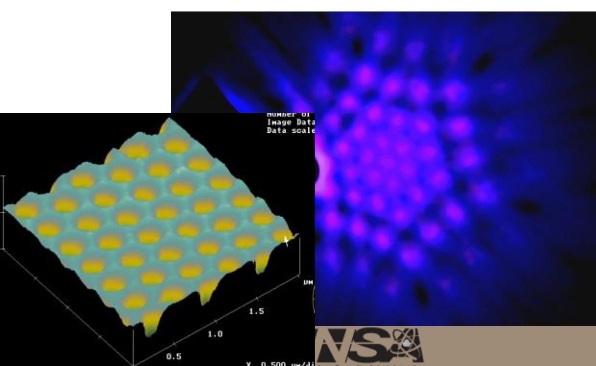


2006-2008: DOE /EERE National Center for SSL

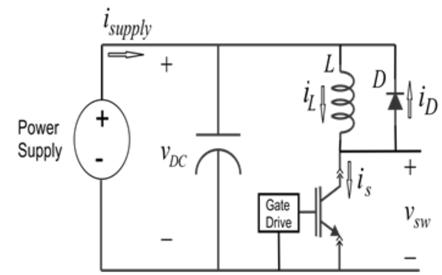
2003-2012: DOE-Funded Collaborations with industry

R&D 100

2000-2004: Grand Challenge LDRD



Our GC LDRD: A New Class of Power Electronics, Based on Materials and Device Science Foundation

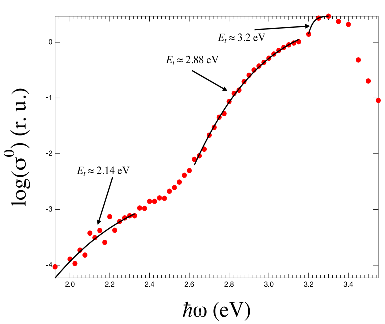


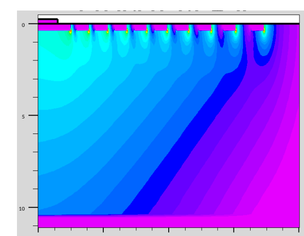
UWBG Epitaxy

Fundamental Physics of Reliability

Power Device Realization

High-Voltage Test





- **Several technical teams closely linked and working towards a common goal**
- **Project initiated October 1, 2014 and will run for three years**

Epitaxial Growth Science for UWBG Materials Synthesis

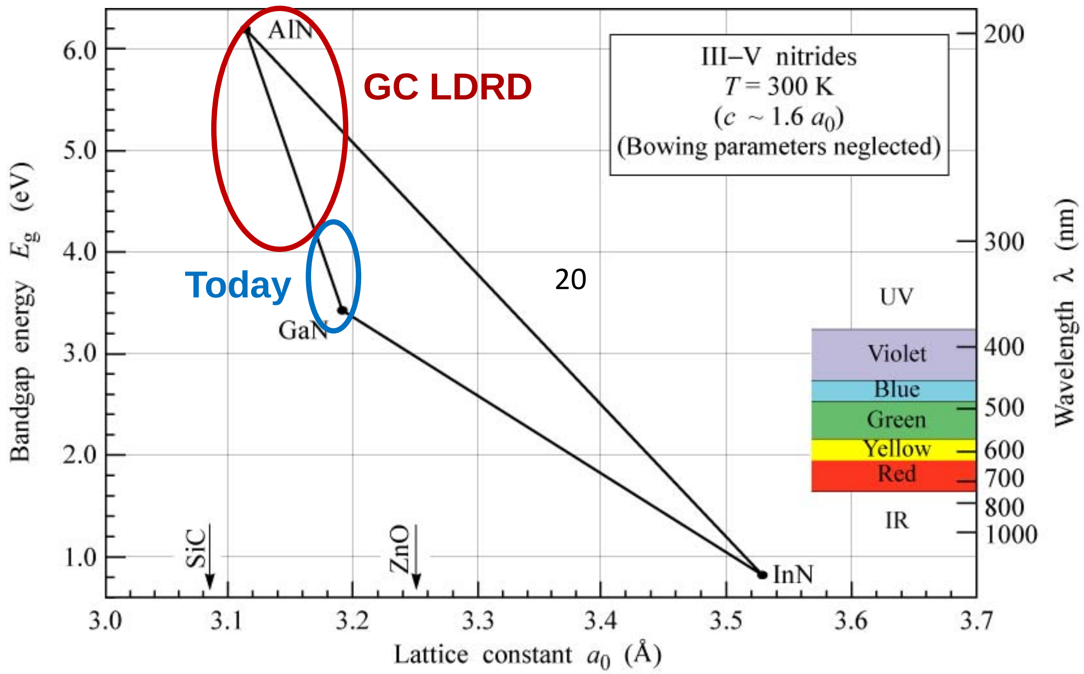


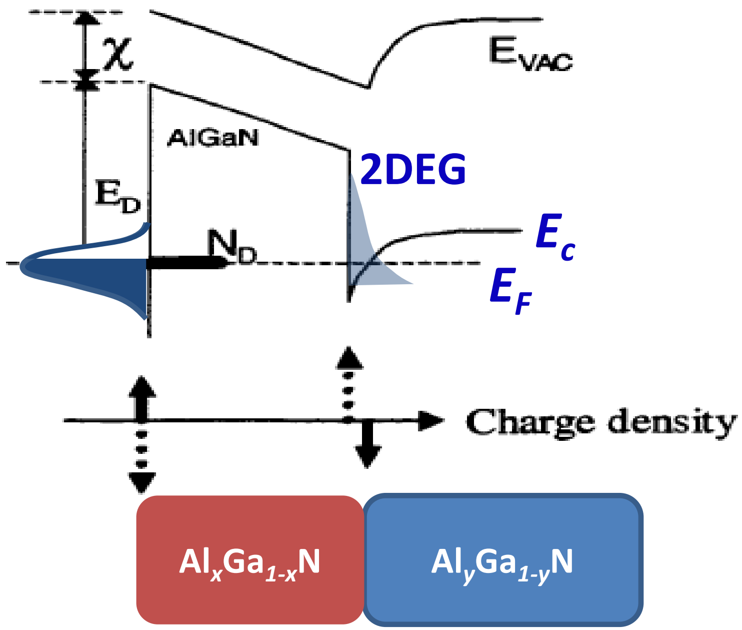
Fig. 12.12. Bandgap energy versus lattice constant of III–V nitride semiconductors at room temperature.

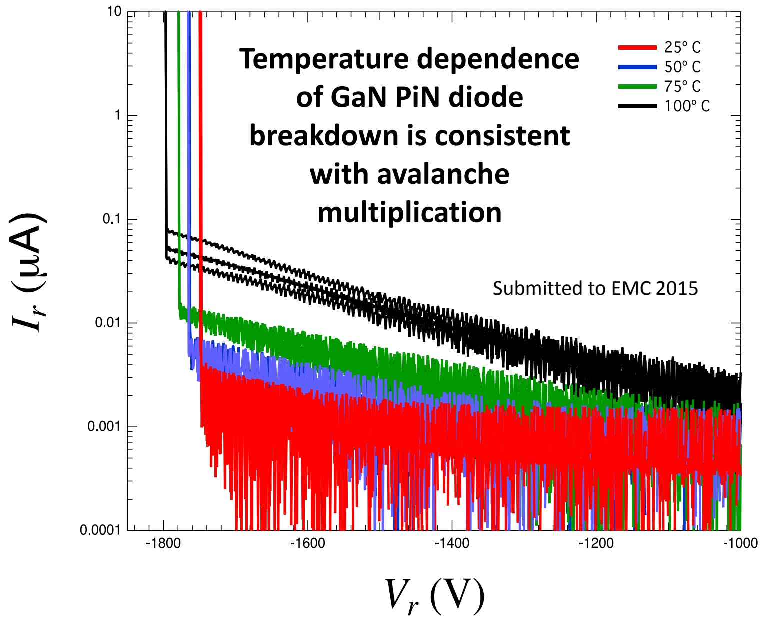
E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

- ***AlGaN with Al > 30%***
- **New high-temperature growth chamber with chemically reacting flow modeling**
- **Strategies for controlling compensating point defects and doping (aligned with Defects Physics thrust)**
- **Epitaxial design for polarization engineering**

Fundamental Physics for State-of-the-Art Performance and Reliability

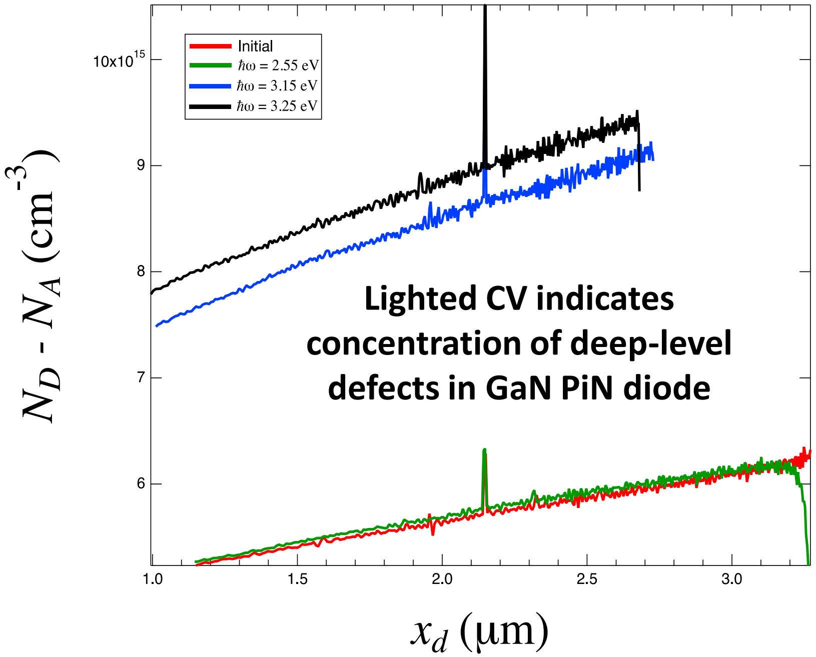
Physics of 2DEG formation in UWBG heterostructures

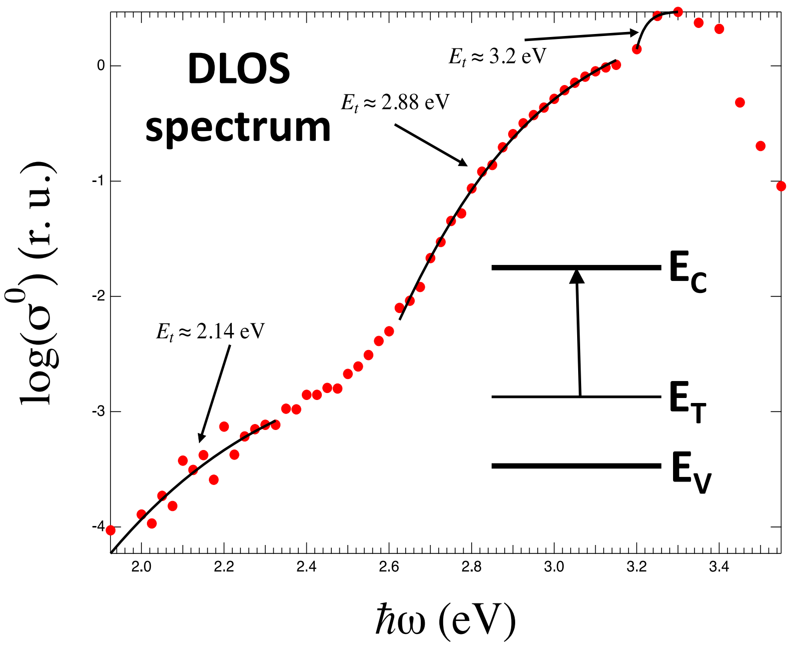




Electrical characterization and device physics analysis

Fundamental Studies of Defect Physics





Sandia has one of only a few systems in the country to characterize deep-level defects throughout the entire bandgap of UWBG semiconductors

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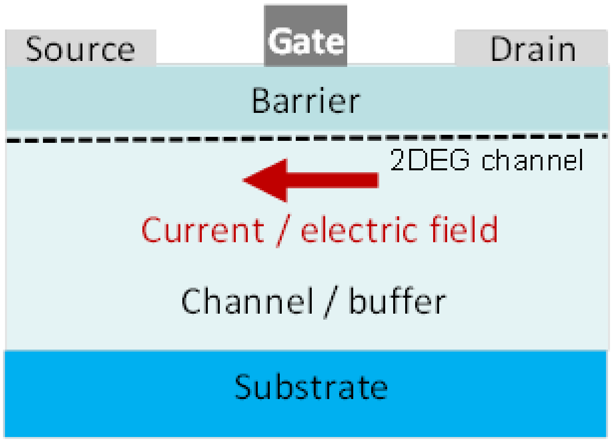
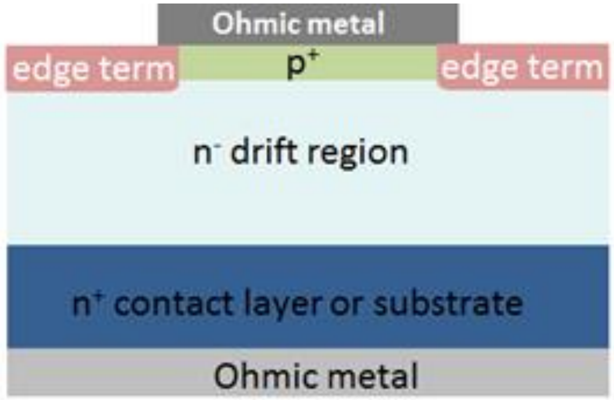
Advanced Concepts, Design, and Fabrication for Novel Power Devices



Lateral device

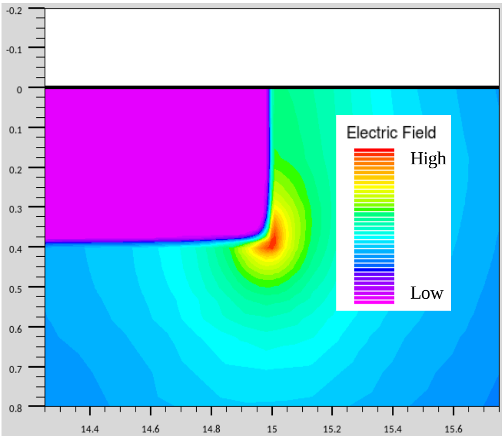
- Advanced gate stack engineering for normally-off operation
- Novel field plate designs for high breakdown voltage
- Thermal properties (experiments and modeling)



Vertical device

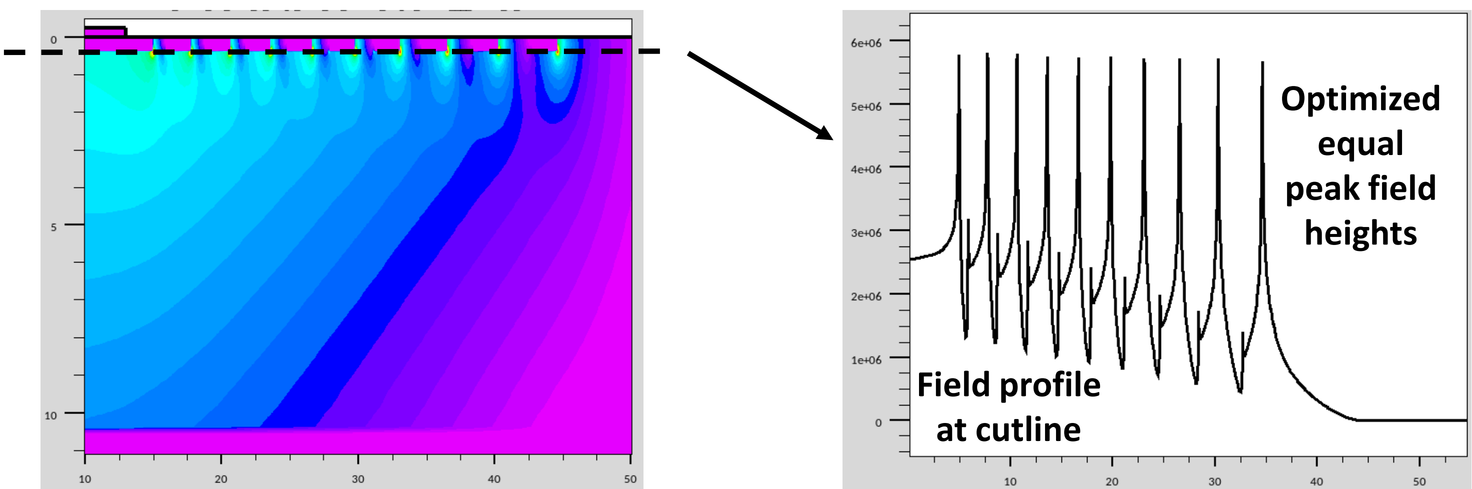
- Growth of thick, low-doped drift layers on various substrates
- Fundamental physics of point and extended defects, carrier transport, and breakdown
- Field termination structures

Device Design and Fabrication



High electric field at corners of doped regions leads to premature breakdown

Numerical simulation of field-termination structures in GaN PiN diode result in optimized design prior to fabrication



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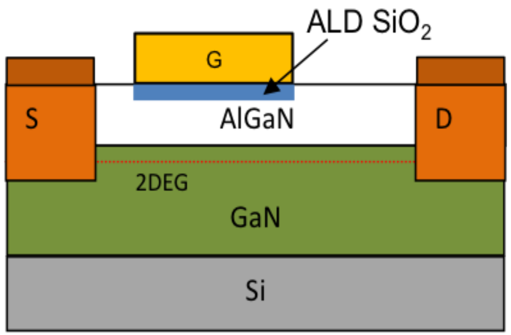
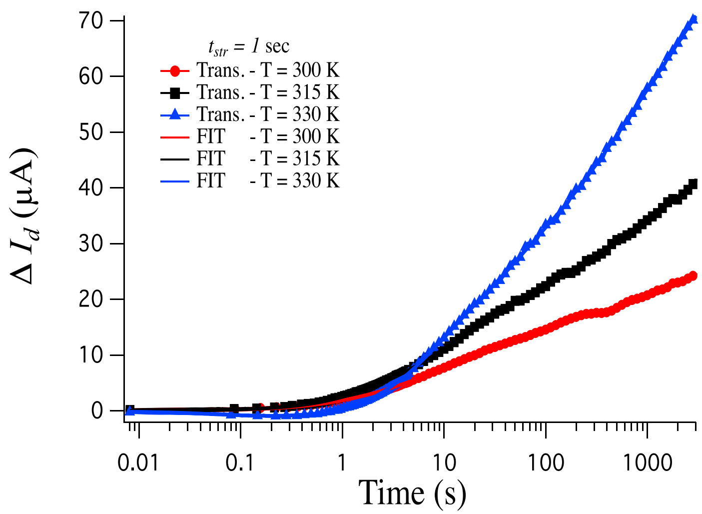
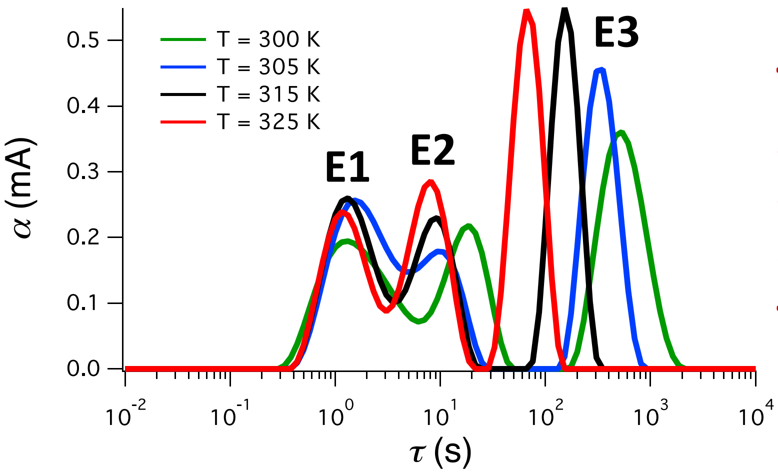
AlGaN/GaN HEMT Reliability



Device structure



Drain current recovery transients and fits following *off*-state electrical stress at different temperatures

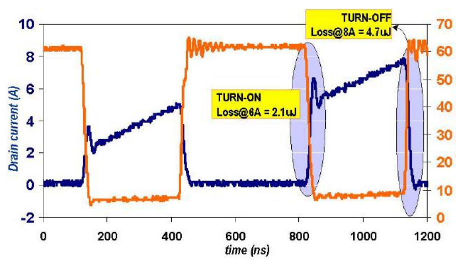


Time constant spectrum from exponential fits to drain current transients

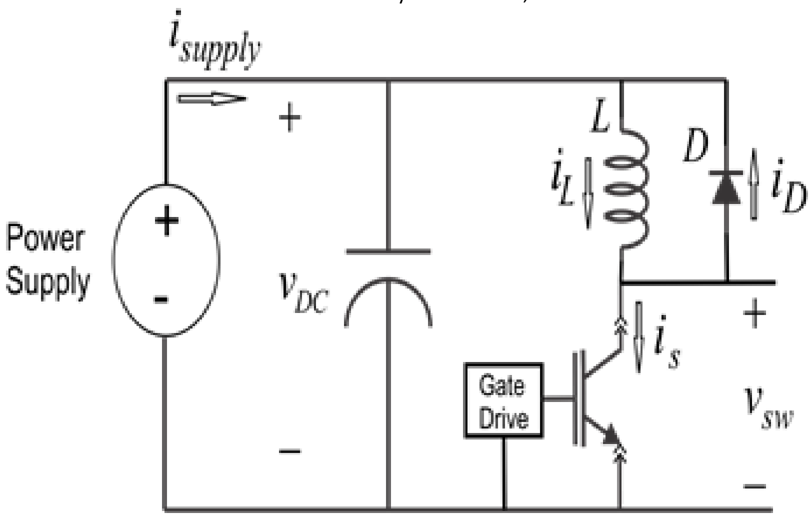
$$\Delta I_D = \sum \alpha_i \left(1 - e^{-t/\tau_i}\right)$$

Submitted to IRPS 2015

High-Voltage DC and Switching Test Characterization

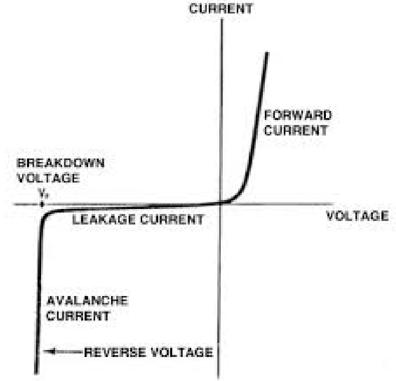


Courtesy of K. Boutros, HRL Labs



HV double pulse test circuit

HV current-voltage tracer



Civilian Application Space for WBG and UWBG Devices

Sandia National Laboratories

Ultra WBG

Vertical SiC

Lateral GaN

Vertical Si

Vertical GaN

Operating Voltage	600 V	1200 V	10s of kV	MV
	Motor drives Electric vehicles Airplanes	PV inverters	Electric grid Electric rail Grid-level energy storage	HV-DC transmission and fault protection

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

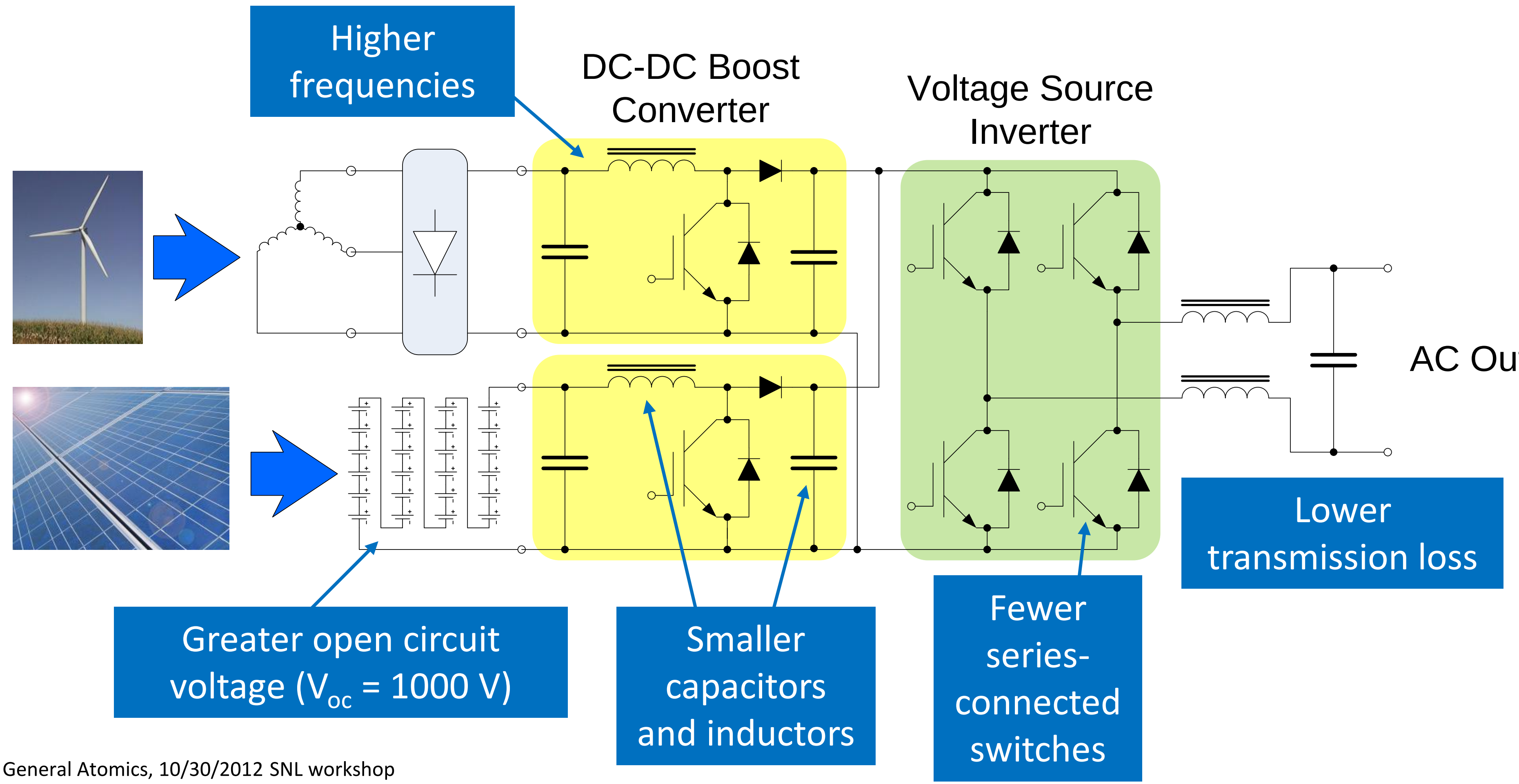
- Higher voltages, lower resistive losses

- AC subsystems to 13.8 kV

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

Example: WBGs and UWBGs for Increased Grid Efficiency and Resiliency

A modern, resilient electric grid with integrated renewable power sources requires power electronics and power inverters



General Atomics, 10/30/2012 SNL workshop

Military Application Space for WBGs and UWBGs: Next-Generation US Navy Power Needs

USS Zumwalt

Electromagnetic Railgun

Higher degree of electrification desired in a SWaP-constrained environment

USS Gerald R. Ford

Questions?

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