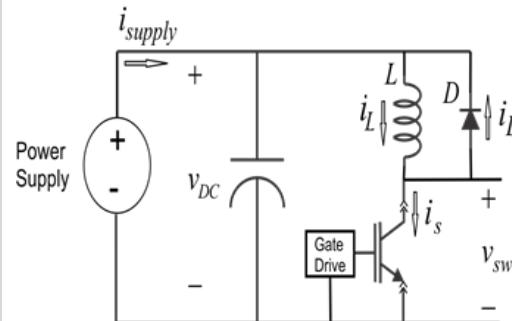
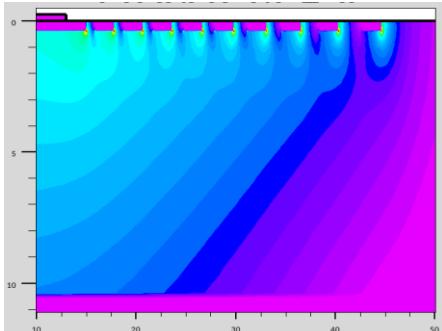
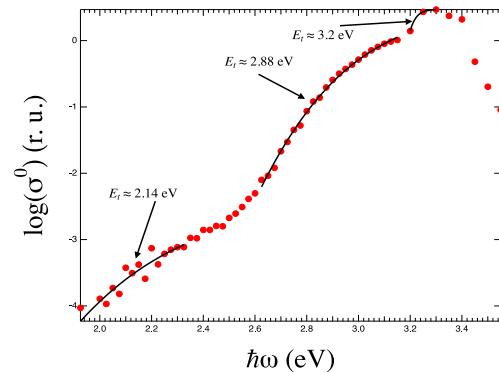


# Ultra-Wide-Bandgap Semiconductors for Power Electronics



SAND2015-1674PE



Presented by:  
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**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**

# 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**

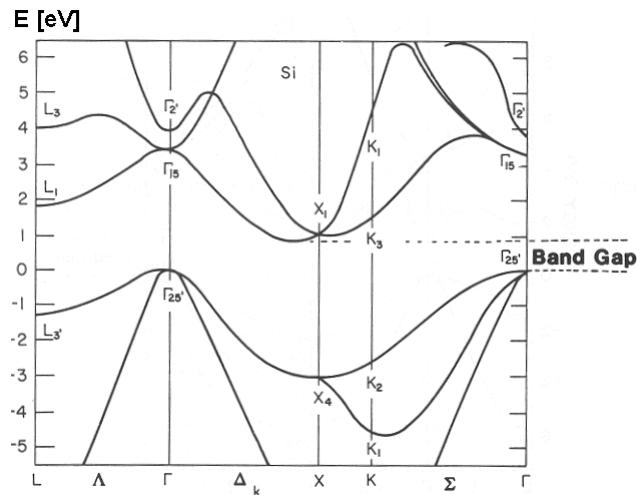
# What are Semiconductors?

## Group IV, III-V, II-VI

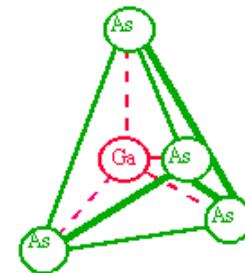
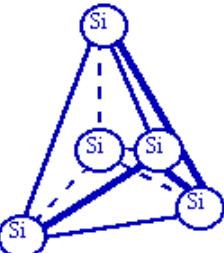
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H	1	He	4.0000
1.0073			
lithium	3	boron	5
Li	4	B	6
6.941	9.0122	C	7
sodium	11	aluminum	13
Na	12	Si	14
22.99	24.305	Al	15
Mg	24.305	16	S
19	20	17	P
K	Ca	18	Cl
39.09	40.078	19	Ar
rubidium	37	21	20
Rb	38	Sc	19
85.446	87.67	Ti	20
strontium	39	22	19
Sr	40	V	21
88.906	91.224	23	Sc
yttrium	41	24	Ti
Y	42	Cr	22
Zr	43	25	V
Nb	44	Fe	23
Mo	45	26	Cr
Tc	46	Co	24
Ru	47	27	Fe
Rh	48	Ni	25
Pd	49	28	Co
Ag	50	29	Co
Cu	51	30	Fe
Zn	52	31	As
Ga	53	32	Se
In	54	33	Se
Sn	55	34	As
In	56	35	Se
Sb	57	36	Kr
Bi	58	37	
Po	59	38	
Pt	60	39	
Au	61	40	
Hg	62	41	
Tl	63	42	
Pb	64	43	
Bi	65	44	
Po	66	45	
Uu	67	46	
Uub	68	47	
Uuu	69	48	
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* Lanthanide series																						
cerium	57	europium	58	neodymium	59	praseodymium	60	thulium	61	samarium	62	ytterbium	63	europium	64	yttrium						
La	138.91	Ce	146.12	Pr	140.91	Nd	144.24	Tm	147.9	Sm	150.36	Ho	155.96	Gd	160.9	Tb						
cerium	89	thulium	90	europium	91	neodymium	92	praseodymium	93	samarium	94	ytterbium	95	europium	96	yttrium						
** Actinide series		actinium	99	thorium	100	protactinium	101	uranyl	102	neptunium	103	plutonium	104	americium	105	curium						
Ac	[227]	99	90	99	91	99	92	93	99	100	95	99	105	96	97	98	99	100	101	102	103	
Ac	232.04	99	231.04	99	230.05	99	227.05	99	231.04	99	230.05	99	227.05	99	231.04	99	230.05	99	227.05	99	231.04	99

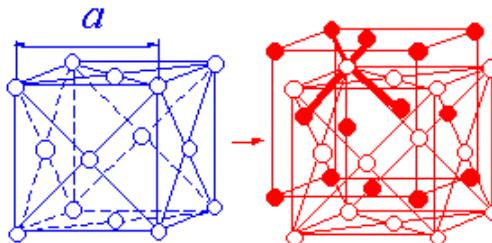
# Band-structure of Si



## Tetrahedral bonding configuration

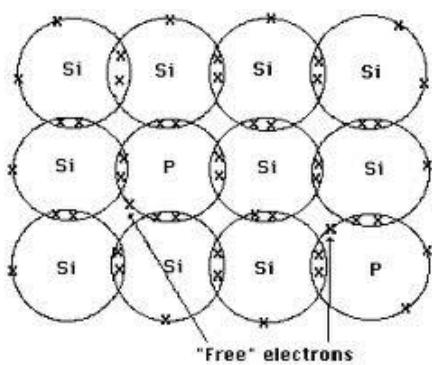


## Face Centered Cubic and Diamond Crystal Structure

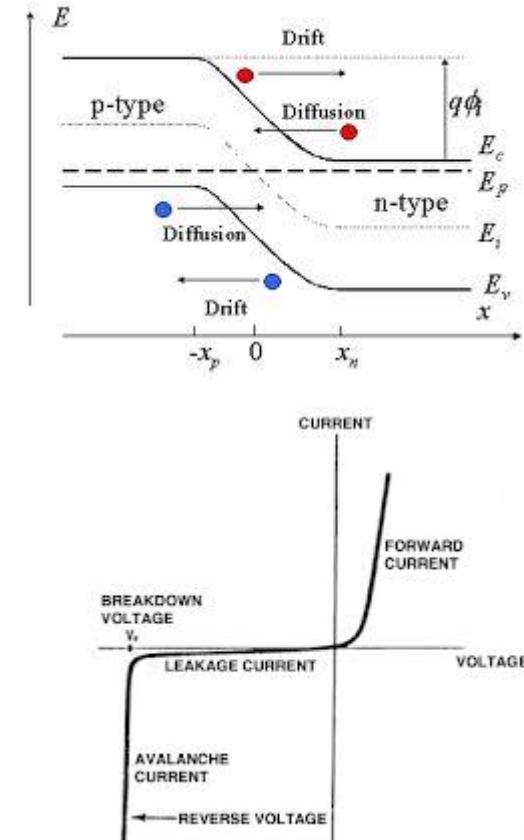
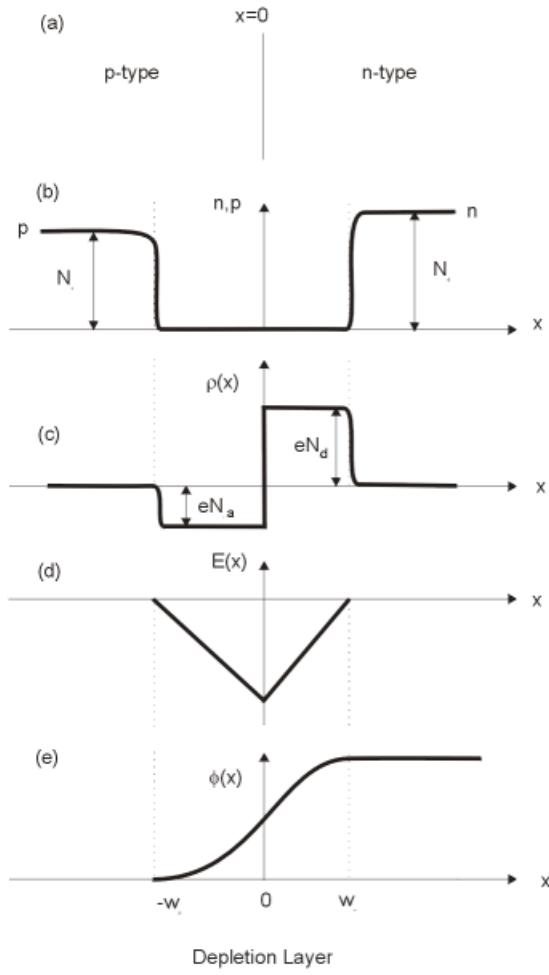


Diamond, Zincblende, or  
Hexagonal (e.g. 2H, 4H, 6H)  
crystal structure

# Doping and pn Junctions

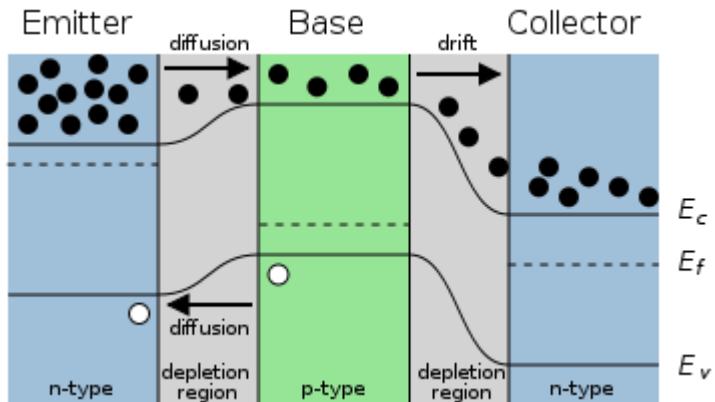


**Doping of Si:**  
**Extra electron = n-type**  
**Missing electron = p-type**

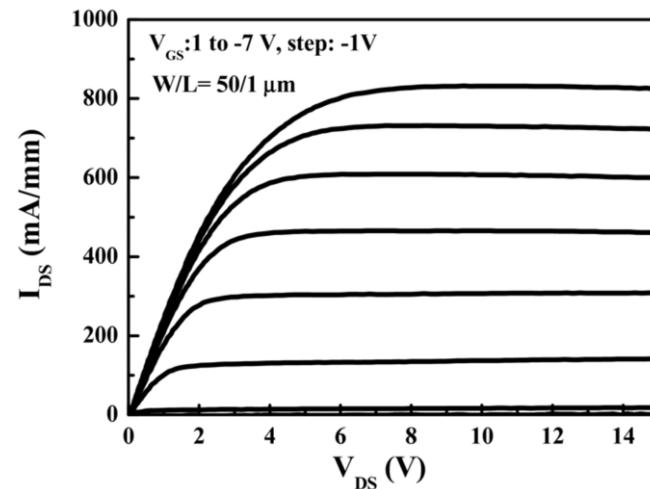
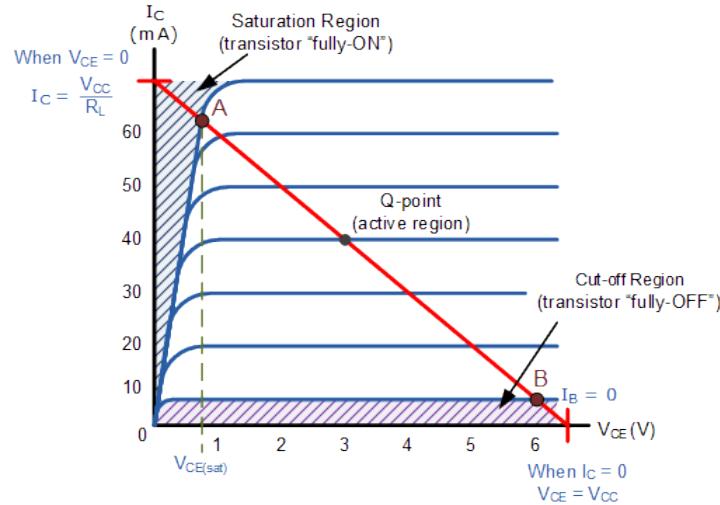
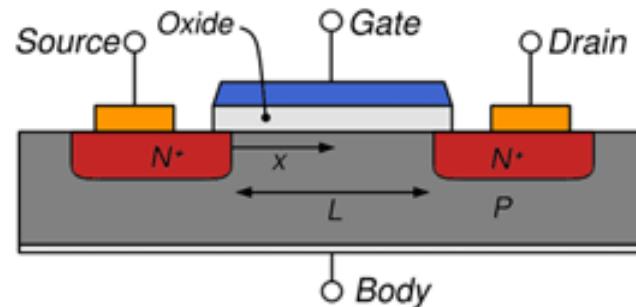


# Bipolar and Field-Effect Transistors

## Bipolar



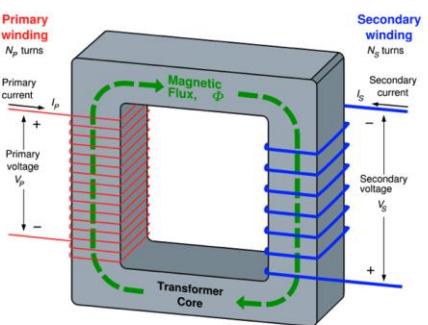
## Field-Effect



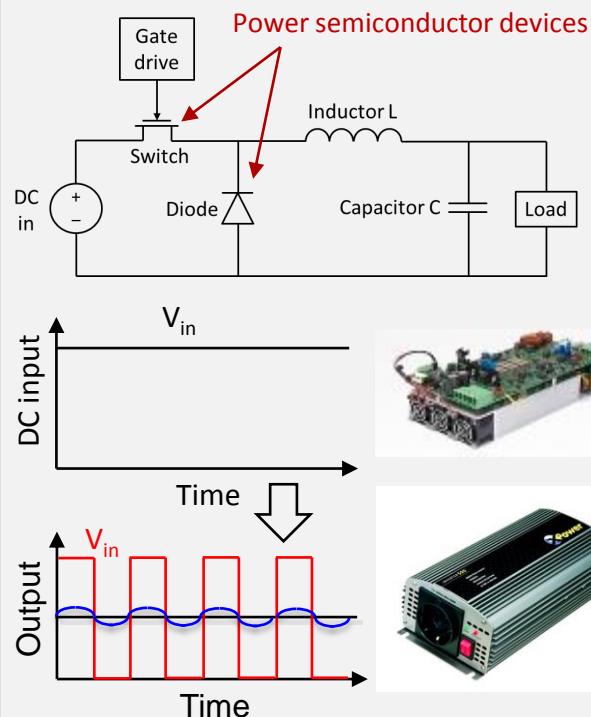
# What Are Power Electronics?

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

## Passive transformers (dumb)



## Power Electronics – Active switching (smart)

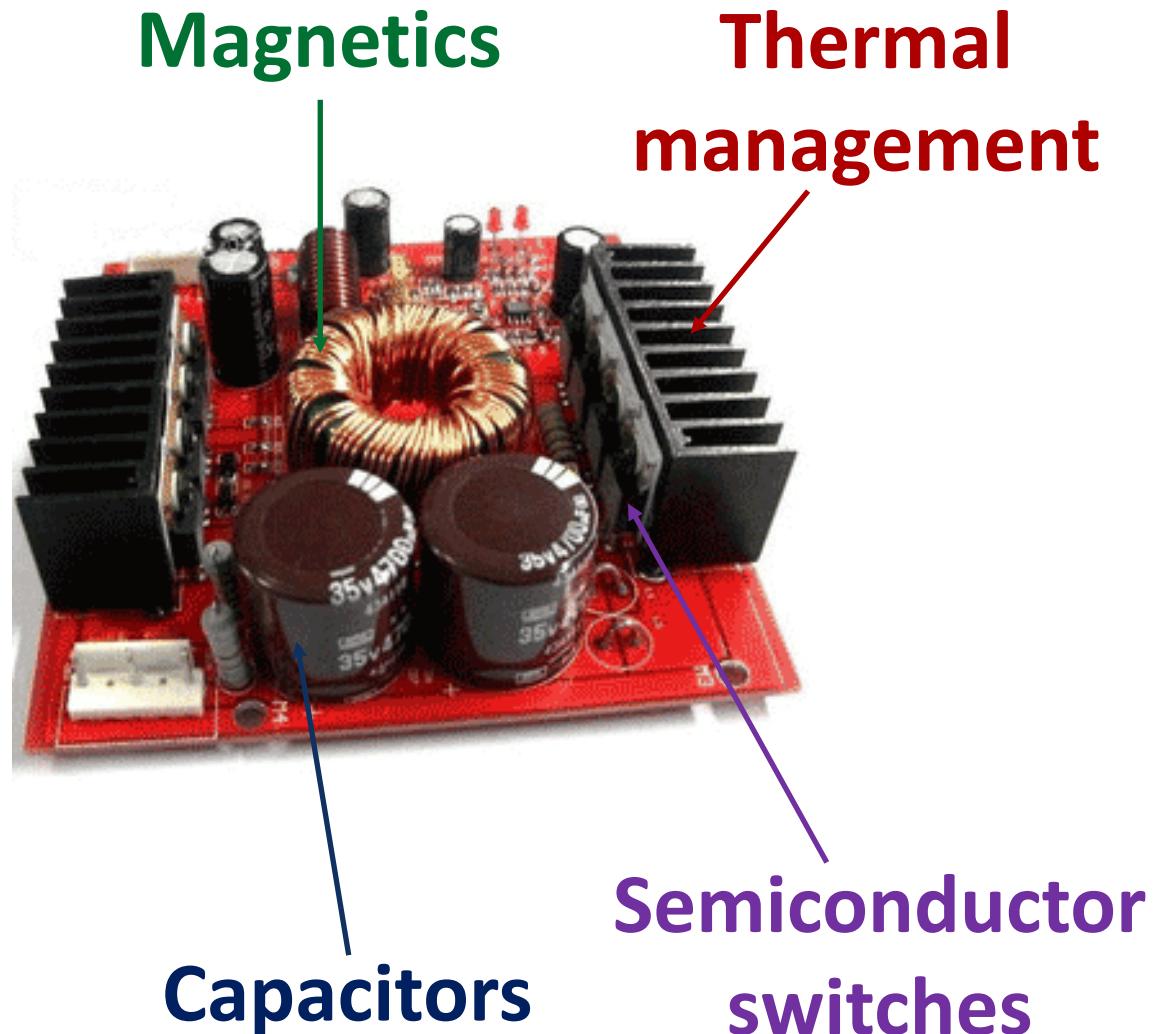


- Current power electronics are limited by the properties of Silicon semiconductor devices
- New system capabilities are enabled by:
  - Higher switching frequency (enables better SWaP)
  - Lower power loss
  - Higher temperature operation

➤ **Motivation for WBG/UWBG semiconductors**

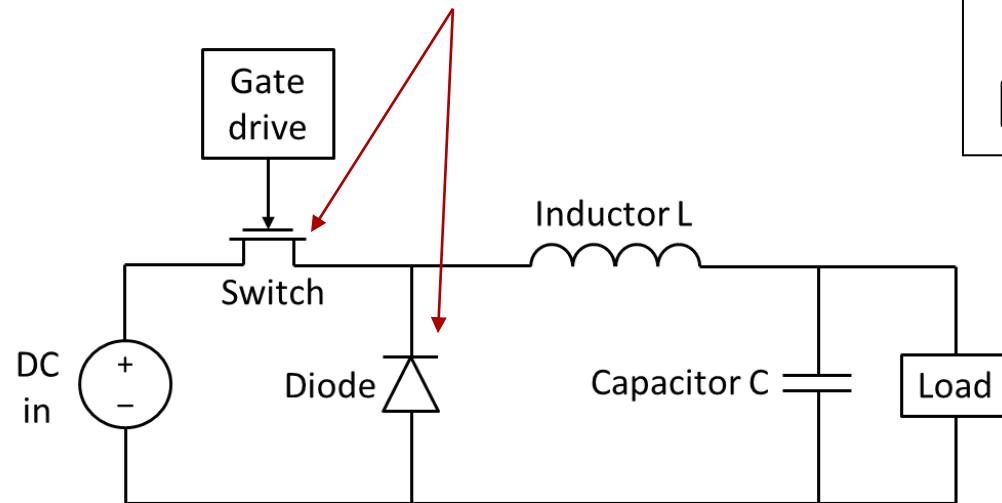
# Power Electronics Volume and Weight Considerations

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

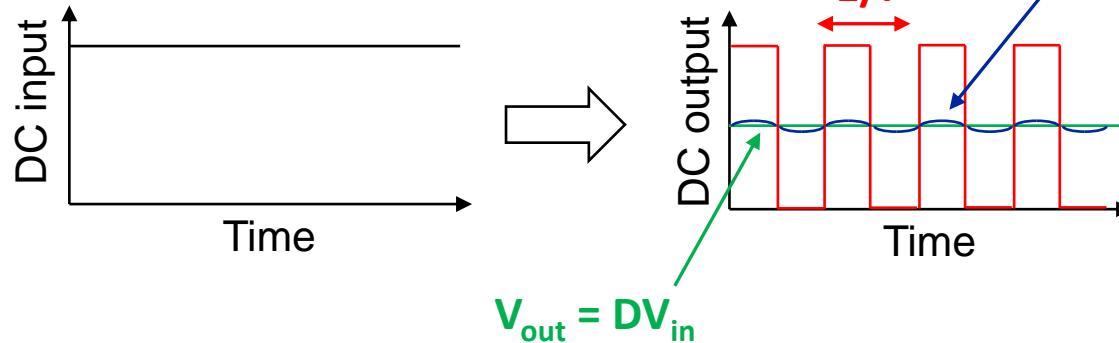


# Higher Switching Frequency Enables Reduction in Passive Element Volume and Weight

## Power semiconductor devices



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



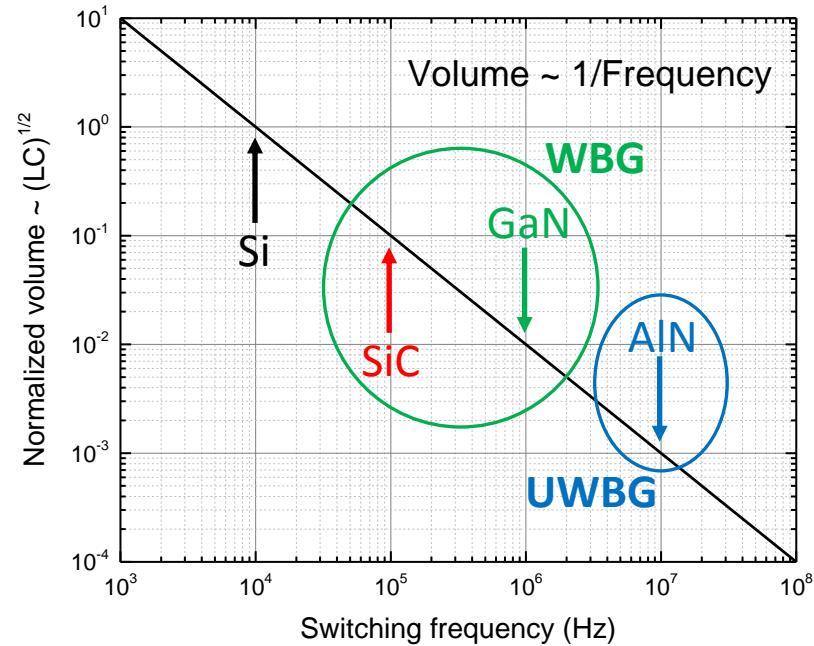
$$\frac{V_{ripple}}{V_{out}} = \frac{1 - D}{8LCf^2}$$

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

# Dramatic Reduction in Power Converter Volume with Increasing Bandgap

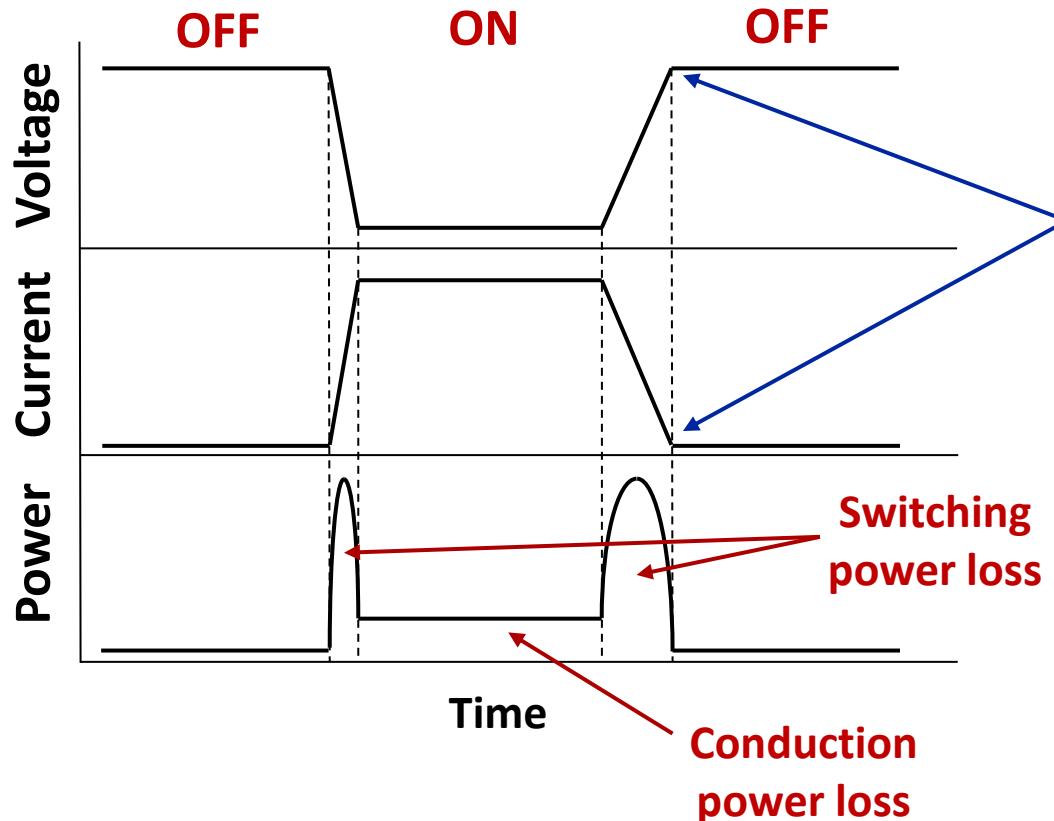


SiC is 10% the volume and weight of Si for equivalent capability (10 kV, 100 A)

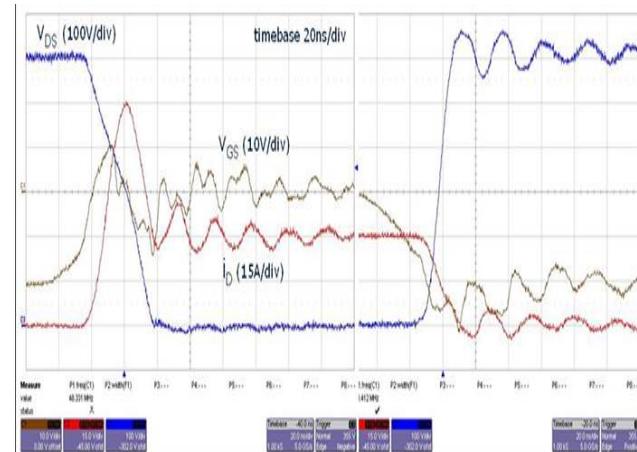


**UWBG PE may result in another order-of-magnitude SWaP improvement compared to WBG PE**

# Heat Generation from Semiconductor Conduction and Switching Losses



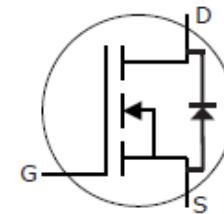
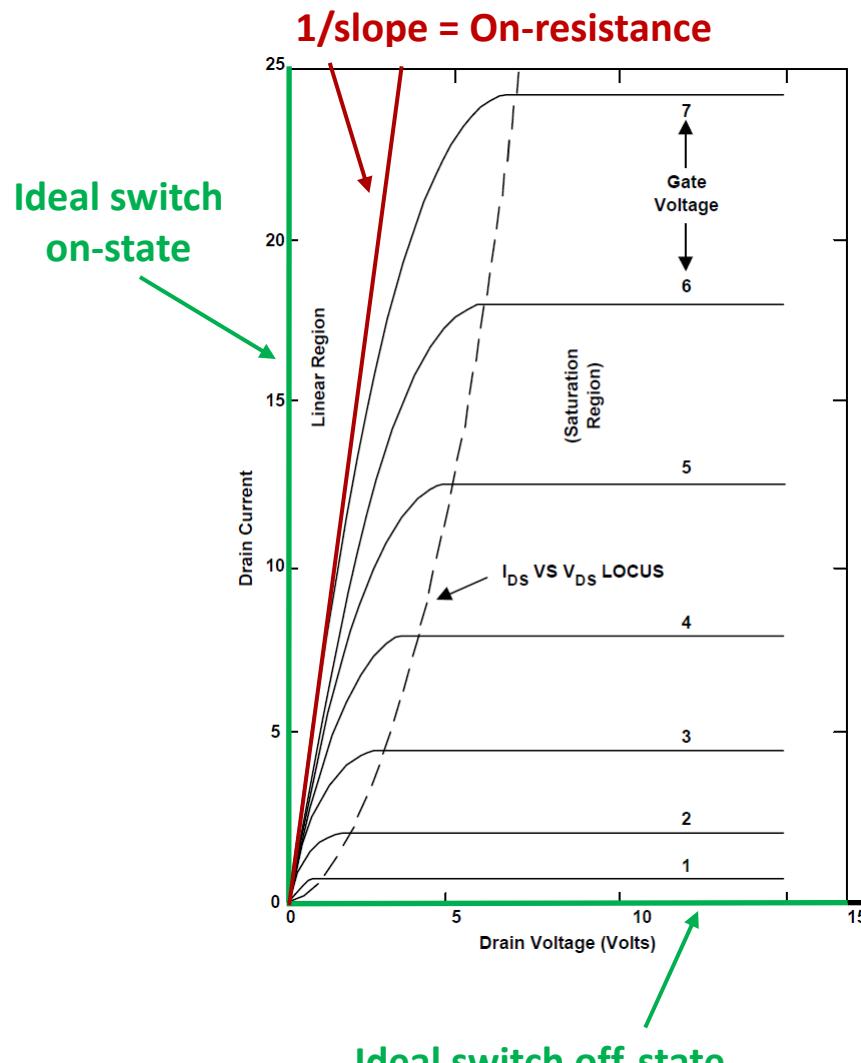
A real circuit will have voltage and current overshoot and oscillations that must be minimized



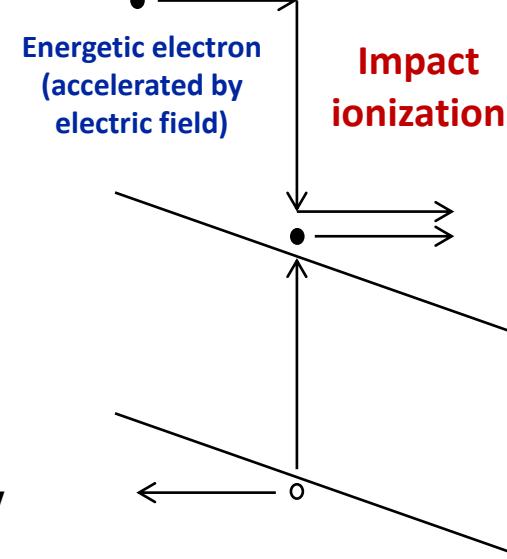
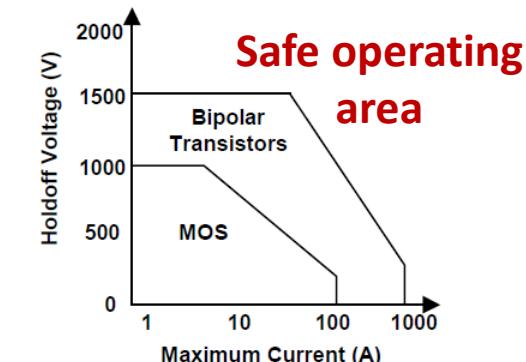
Minimum ON-state loss: *Need low  $R_{on}$*

Minimum switching loss: *Need fast switching transients*

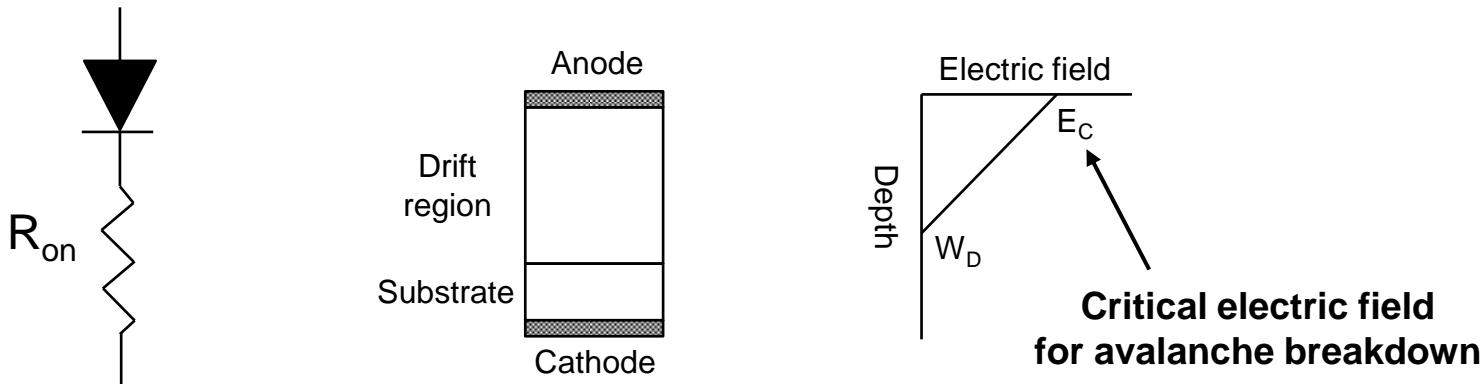
# Semiconductor Devices Are *NOT* Ideal Switches



Avalanche  
breakdown



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

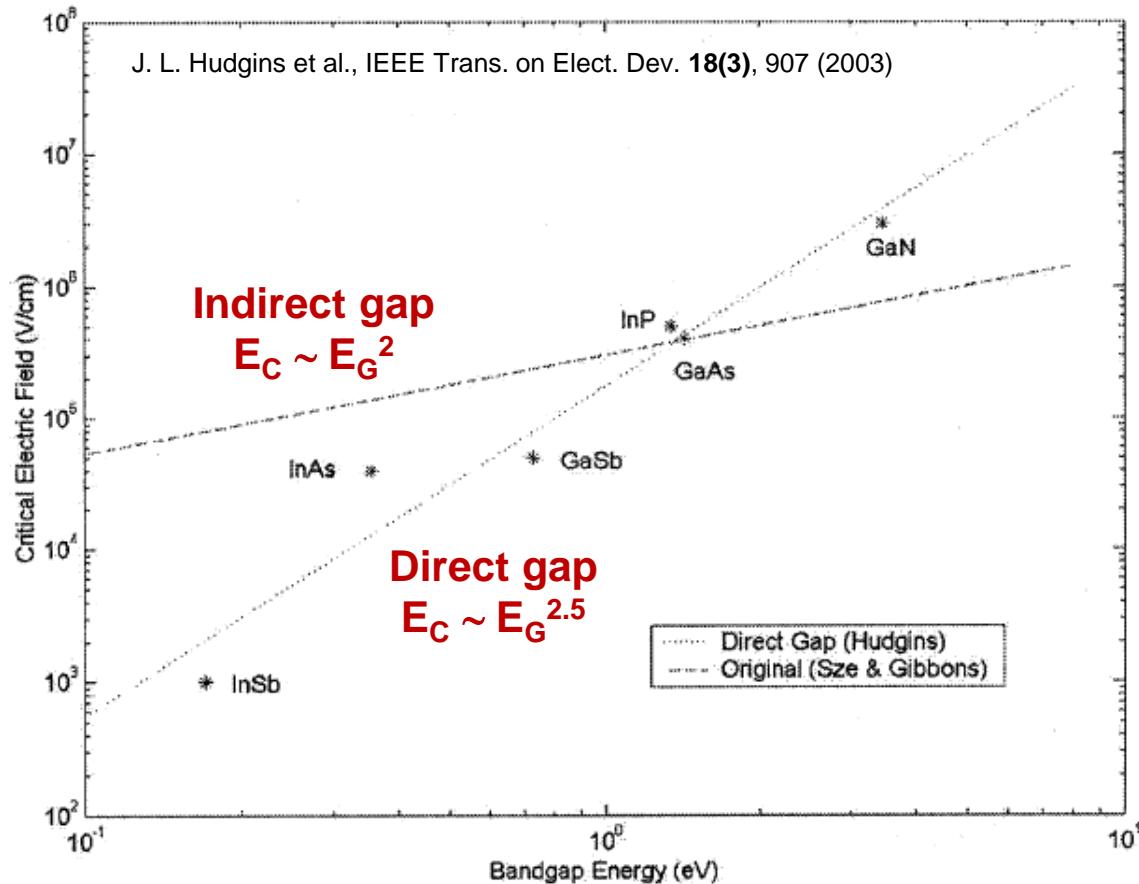


- Off-state: Integrate electric field to get breakdown voltage:  $V_B = W_D E_C / 2$  (1)
- Gauss' law:  $\epsilon E_C = q N_D W_D$  (2)
- On-state: Current transport due to carrier drift, resistance  $R_{on} = W_D / \sigma A$   
Conductivity  $\sigma = q \mu_n n = q \mu_n N_D$  assuming complete dopant ionization  
Specific on-resistance  $R_{on,sp} = R_{on} A = W_D / \sigma \rightarrow R_{on} A = W_D / q \mu_n N_D$  (3)
- Combining (1) and (2) gives dependence of  $V_B$  on  $N_D$  and  $E_C$ :  $V_B = \epsilon E_C^2 / 2qN_D$
- Combining (1), (2), and (3) one obtains the unipolar “figure-of-merit”:  
 $R_{on,sp} = 4V_B^2 / \epsilon \mu_n E_C^3 \rightarrow V_B^2 / R_{on,sp} = \epsilon \mu_n E_C^3 / 4$ 

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



$$E_G(\text{GaN})/E_G(\text{Si}) = 3.4/1.1 = 3.1$$

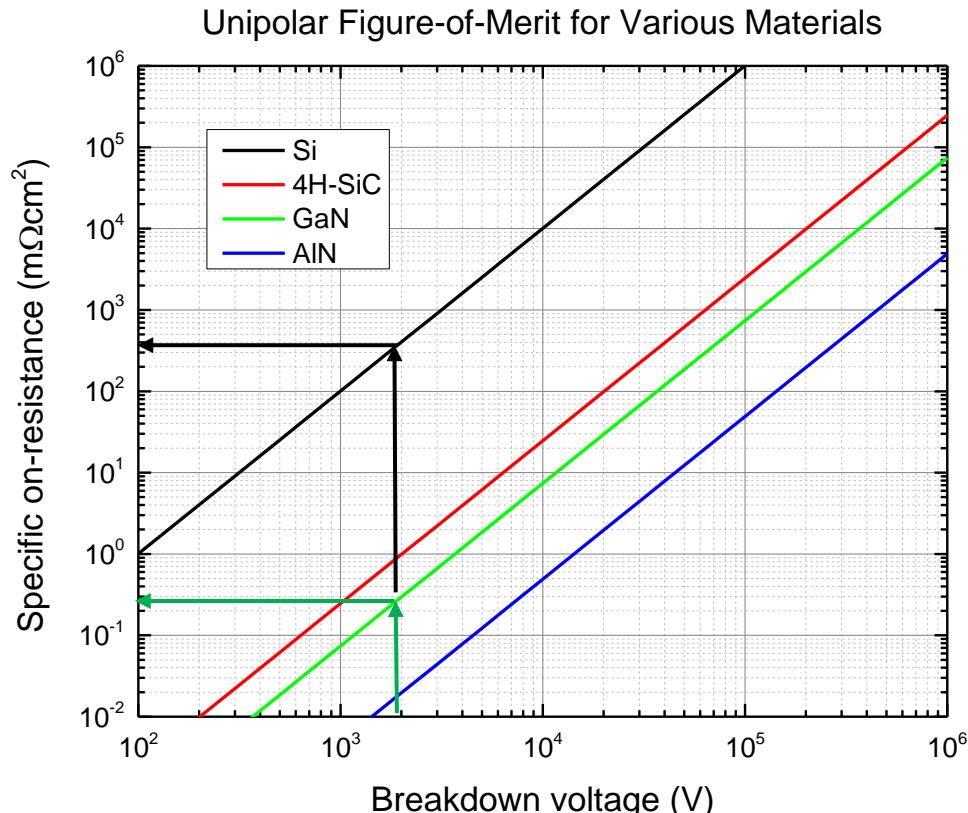
$$E_C(\text{GaN})/E_C(\text{Si}) \approx 3.1^2 = 9.6$$

Unipolar FOM:

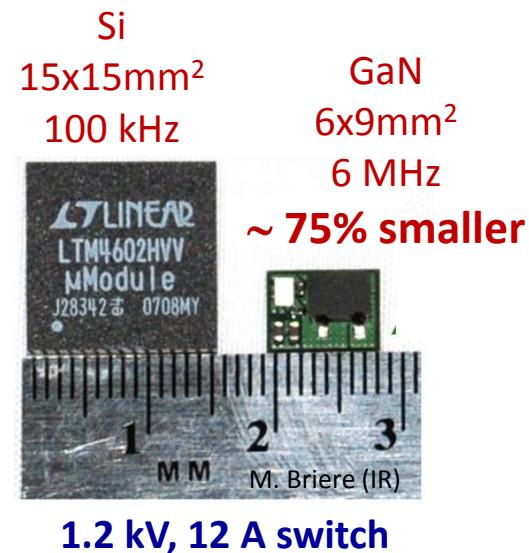
$$\text{FOM} = V_B^2/R_{\text{on,sp}} \sim E_C^3$$

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

# How Do WBGs and UWBGs Lead to Higher Switching Frequency and Lower 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*

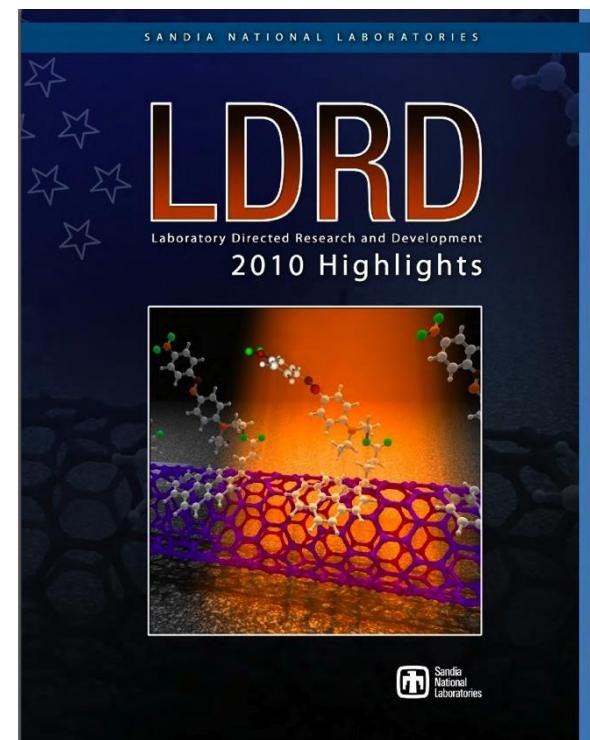


*The scaling that results from the properties of WBG and UWBG materials can be utilized to optimize for switching frequency, conduction loss, and switching loss*

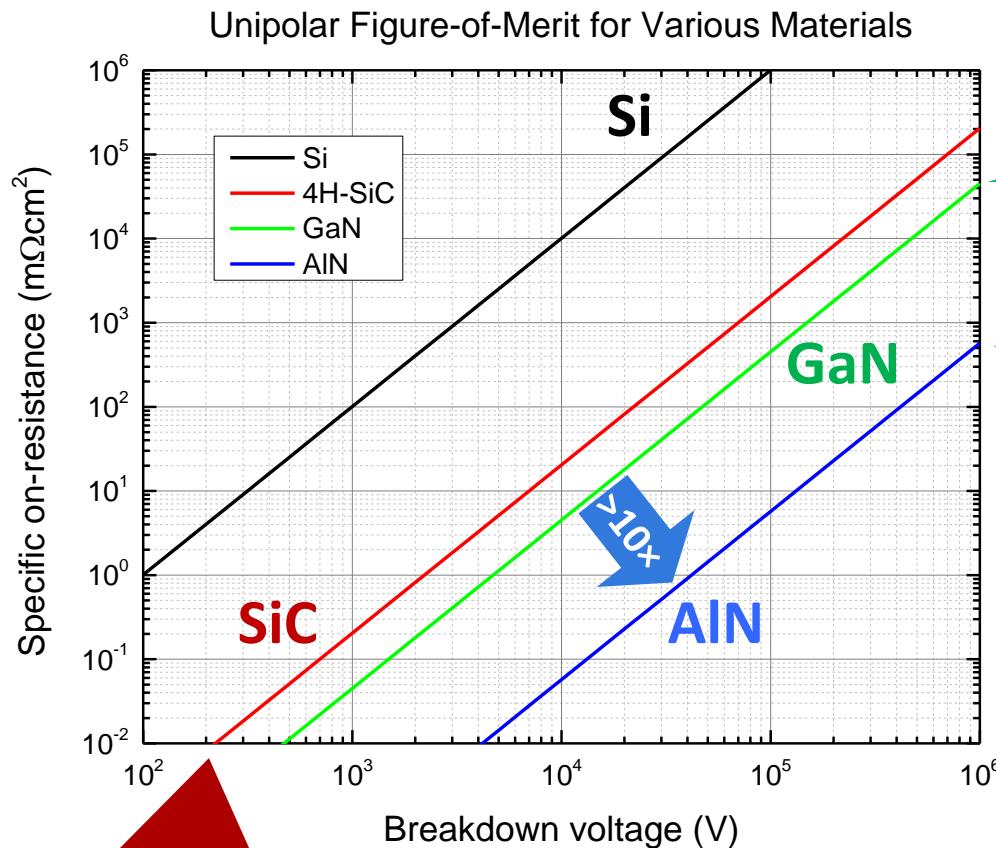
# Sandia's LDRD Program

## 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



**SiC**  
Many commercial devices available

**GaN**  
Lateral devices fairly mature  
Vertical devices emerging

**UWBG Grand Challenge**  
*Unexplored space*  
*Unprecedented performance*

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

Property	Conventional		WBG		UWBG
	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

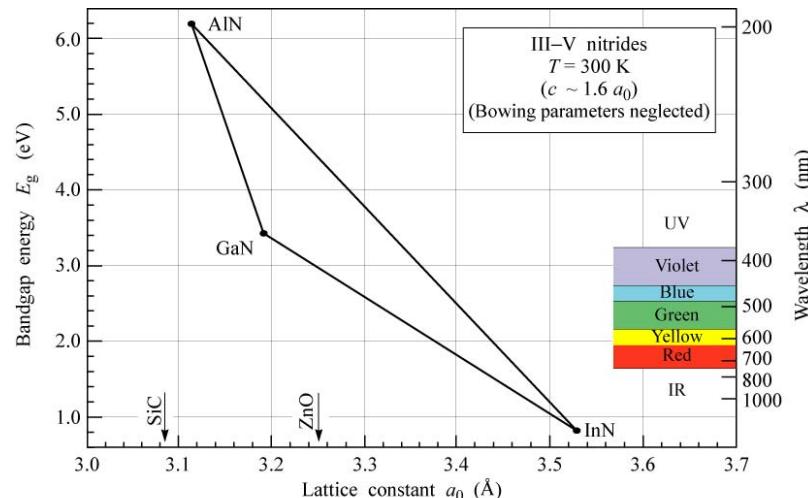
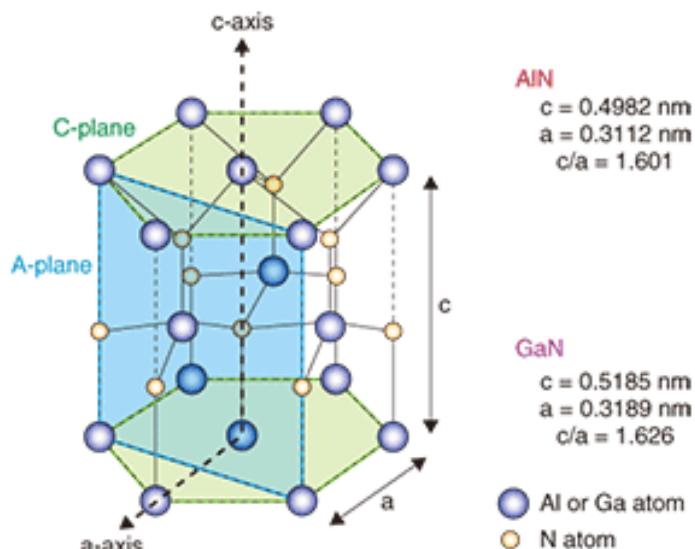


Fig. 12.12. Bandgap energy versus lattice constant of III-V nitride semiconductors at room temperature.

E. F. Schubert  
*Light-Emitting Diodes* (Cambridge Univ. Press)  
[www.LightEmittingDiodes.org](http://www.LightEmittingDiodes.org)

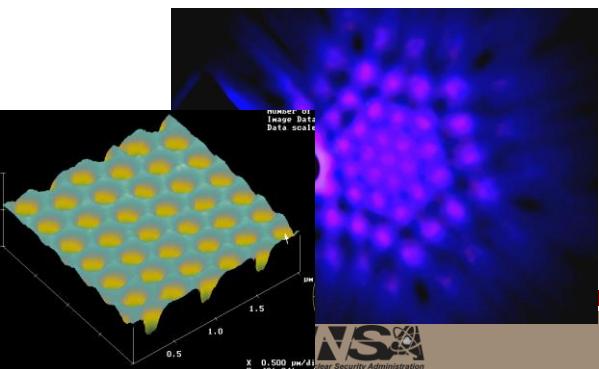
# This Project Builds on 15 Years of Forefront Wide-Bandgap Research at Sandia

**1999-2006:**

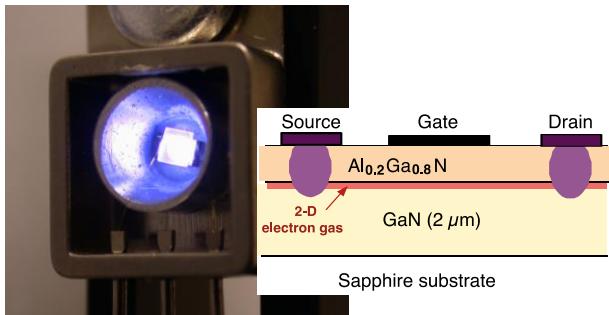
*Comprehensive US Technology Roadmaps*



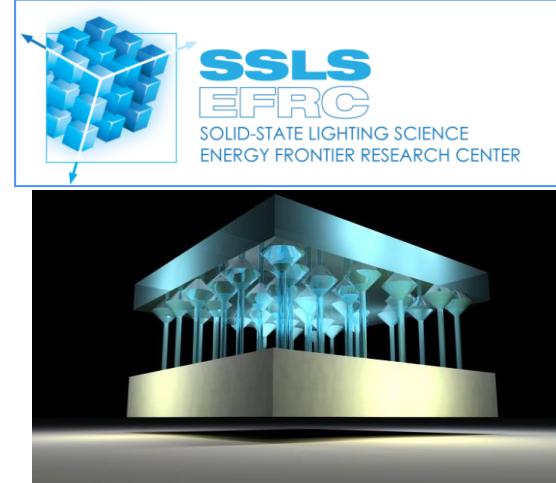
**2000-2004: Grand Challenge LRD**



**2003-2007: high power amplifiers, UV emitters**



**2009-2014: DOE EFRC for SSL Science**



**2006-2008: DOE /EERE National Center for SSL**



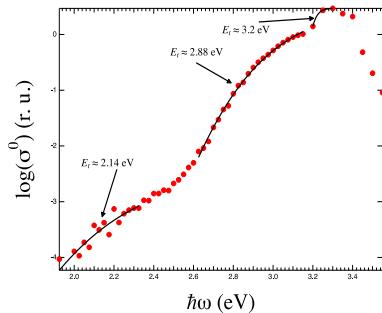
**2003-2012: DOE-Funded Collaborations with industry**



**GeneSiC SiC Thyristors**



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

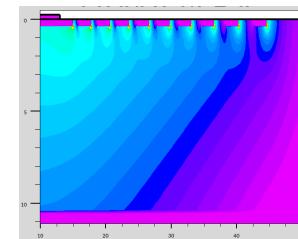
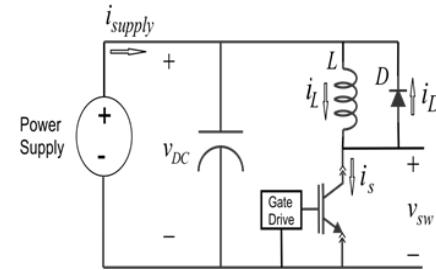


**Fundamental  
Physics of  
Reliability**

**UWBG Epitaxy**

**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

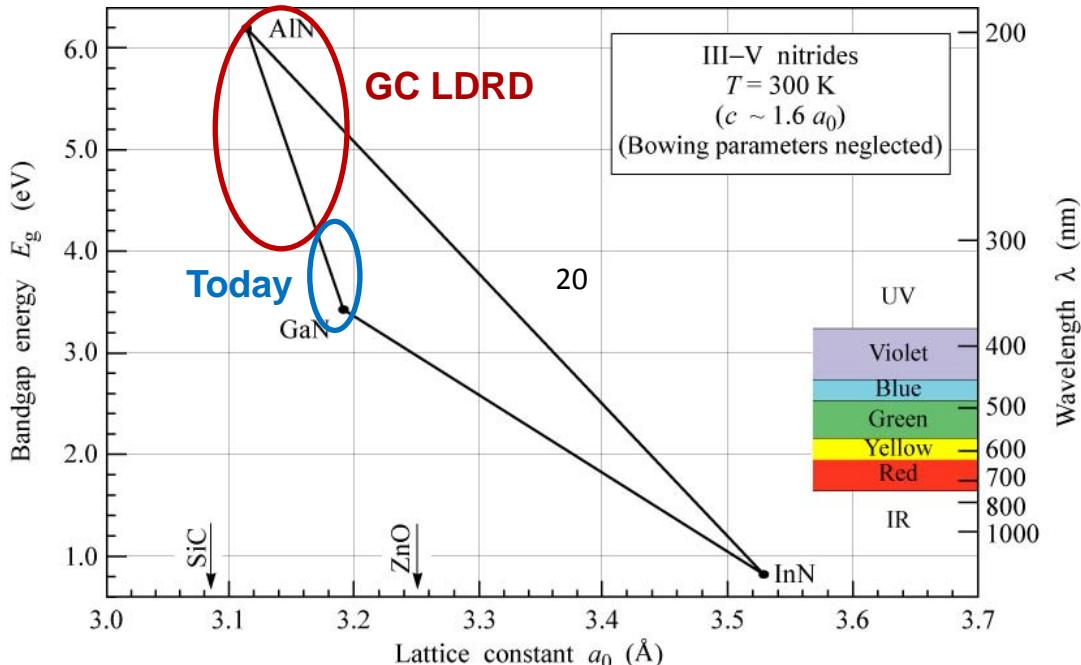


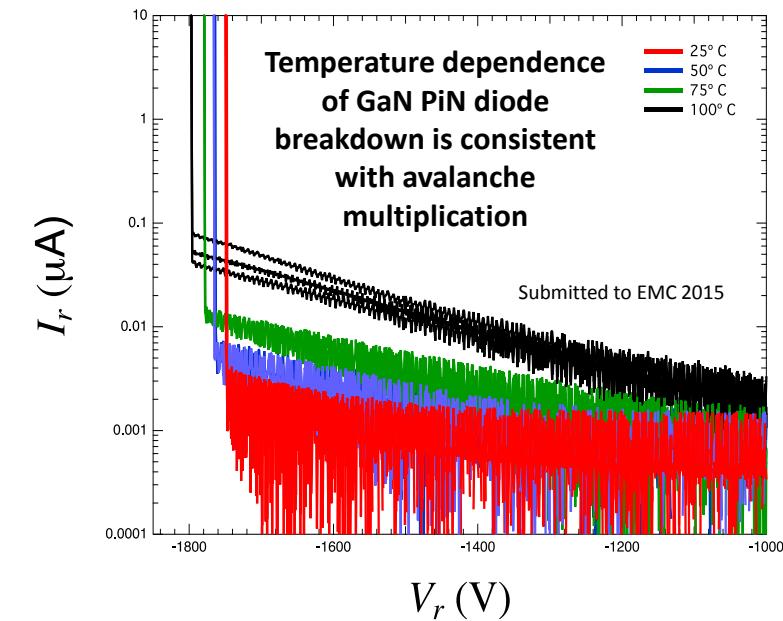
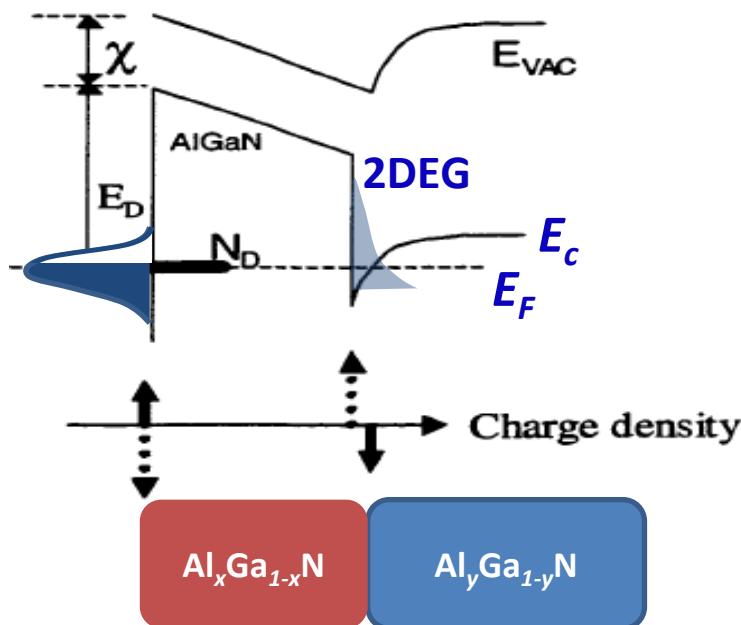
Fig. 12.12. Bandgap energy versus lattice constant of III-V nitride semiconductors at room temperature.

- **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**

E. F. Schubert  
*Light-Emitting Diodes* (Cambridge Univ. Press)  
[www.LightEmittingDiodes.org](http://www.LightEmittingDiodes.org)

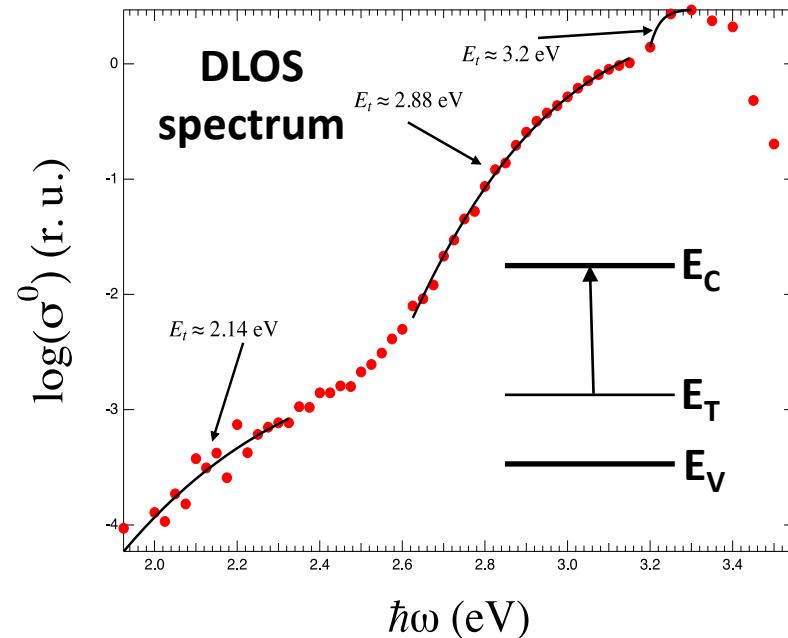
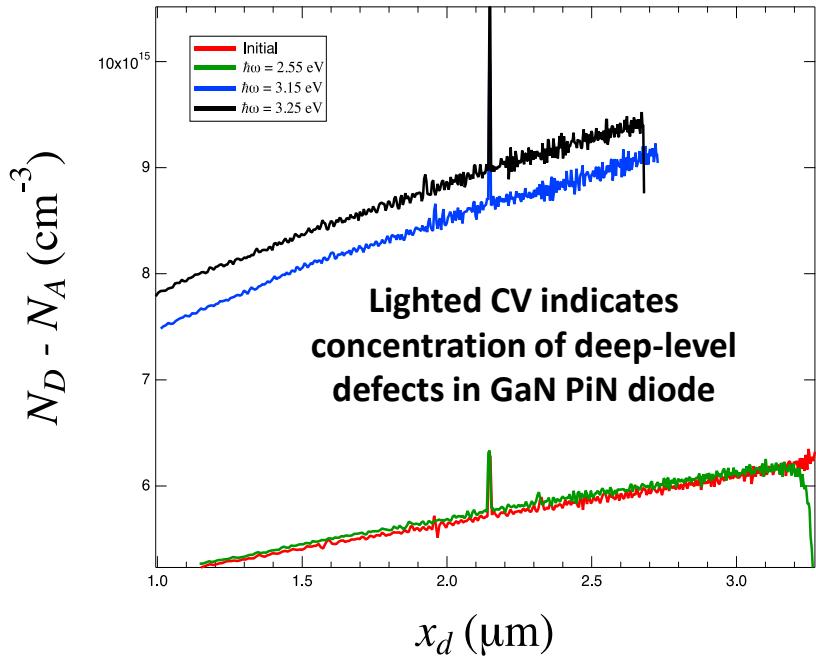
# Fundamental Physics for State-of-the-Art Performance and Reliability

## Physics of 2DEG formation in UWBG heterostructures



Electrical characterization and device physics analysis

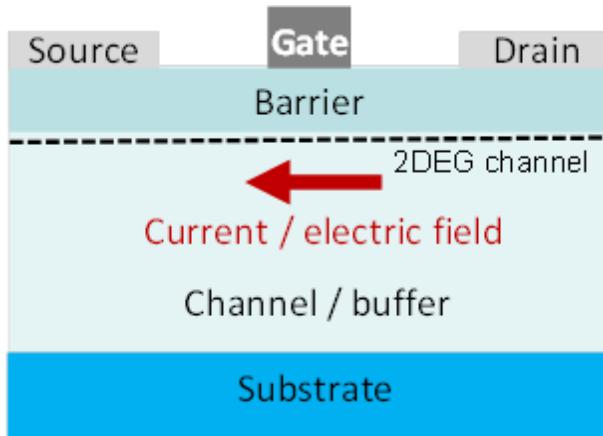
# Fundamental Studies of Defect Physics



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

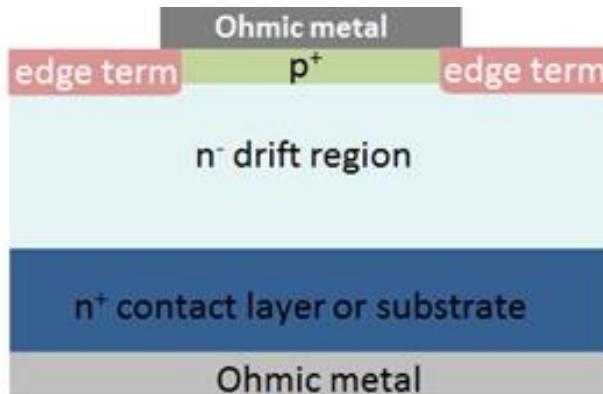
Submitted to EMC 2015

# Advanced Concepts, Design, and Fabrication for Novel Power Devices



## Lateral device

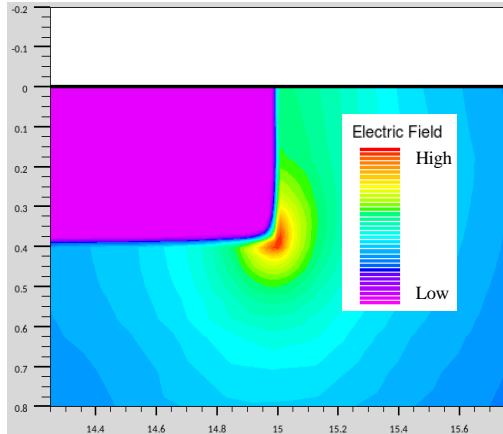
- Advanced gate stack engineering for normally-off operation
- Novel field plate designs for high breakdown voltage
- Thermal properties (experiments and modeling)



## Vertical device

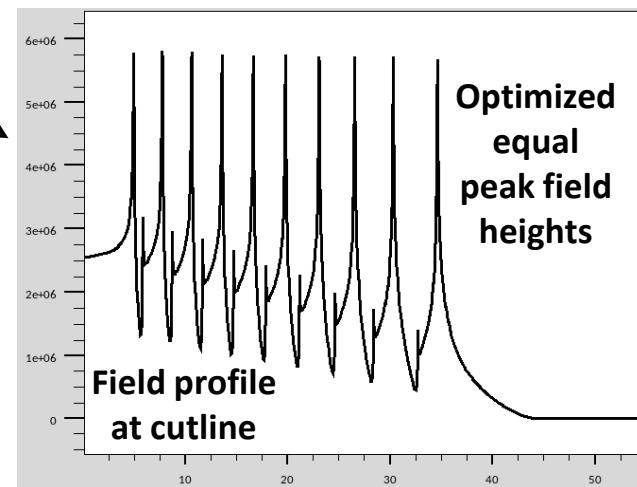
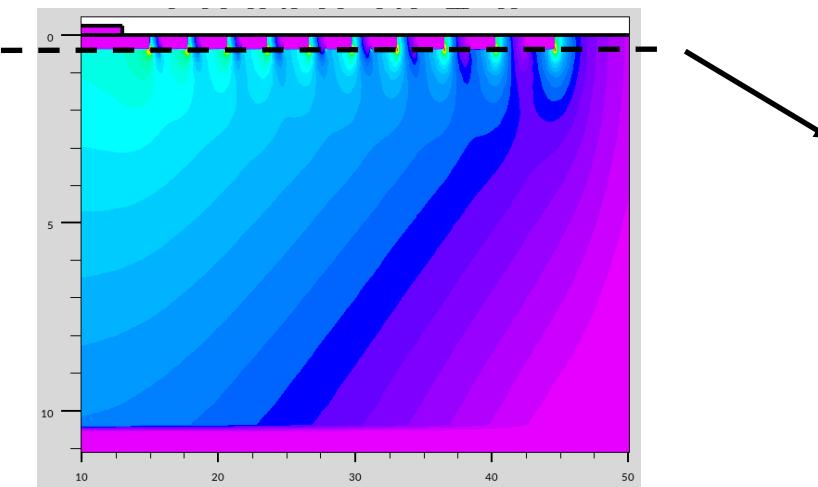
- Growth of thick, low-doped drift layers on various substrates
- Fundamental physics of point and extended defects, carrier transport, and breakdown
- Field termination structures

# Device Design and Fabrication



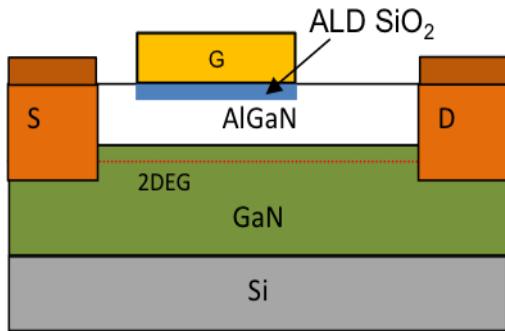
High electric field at corners of doped regions leads to premature breakdown

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

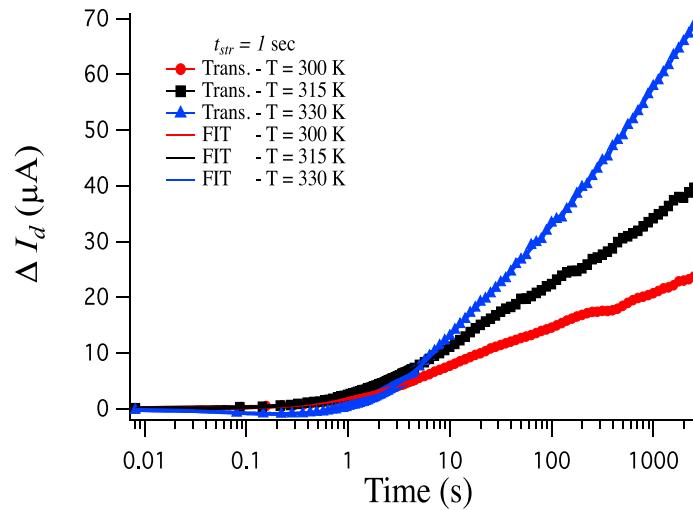


Submitted to EMC 2015

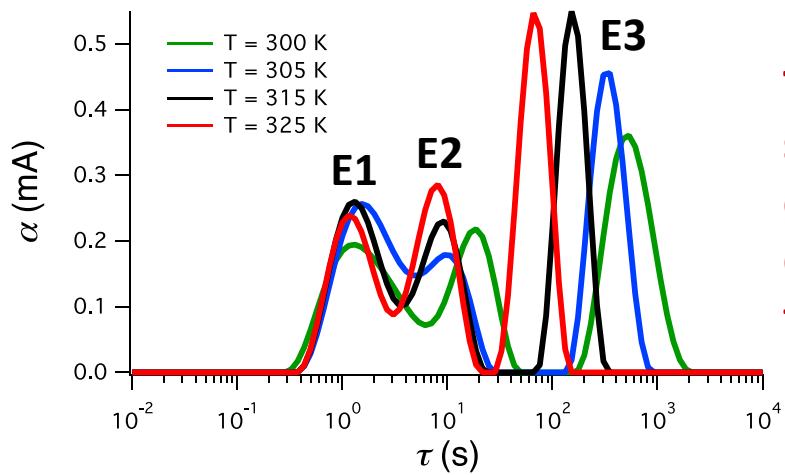
# AlGaN/GaN HEMT Reliability



Device structure



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

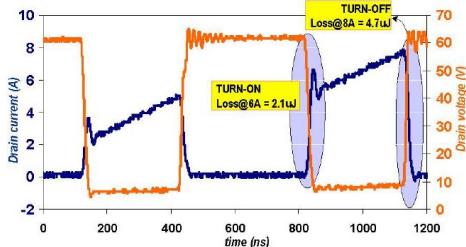


Time constant spectrum from exponential fits to drain current transients

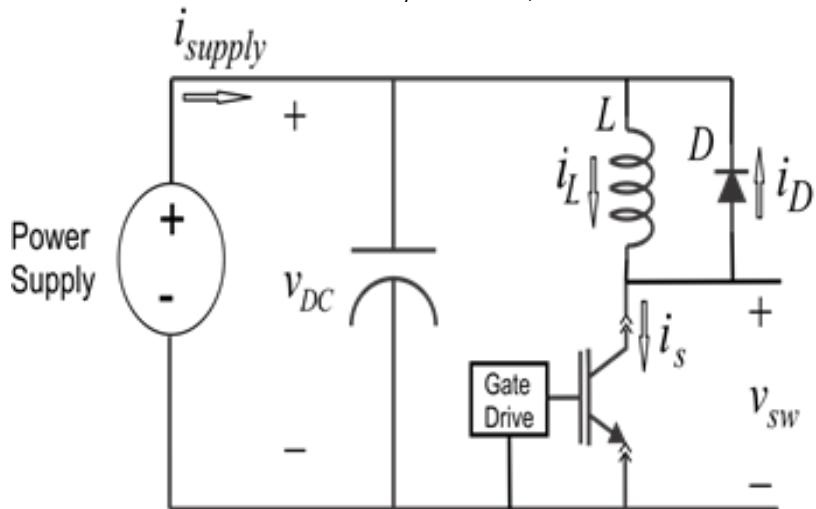
$$\Delta I_D = \sum \alpha_i (1 - e^{-t/\tau_i})$$

Submitted to IRPS 2015

# High-Voltage DC and Switching Test Characterization

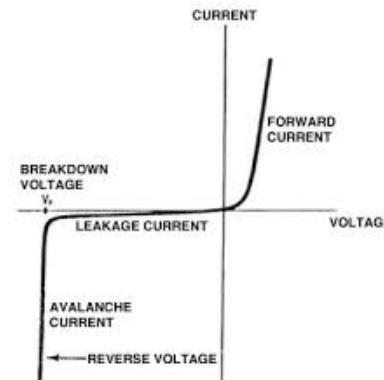


Courtesy of K. Boutros, HRL Labs

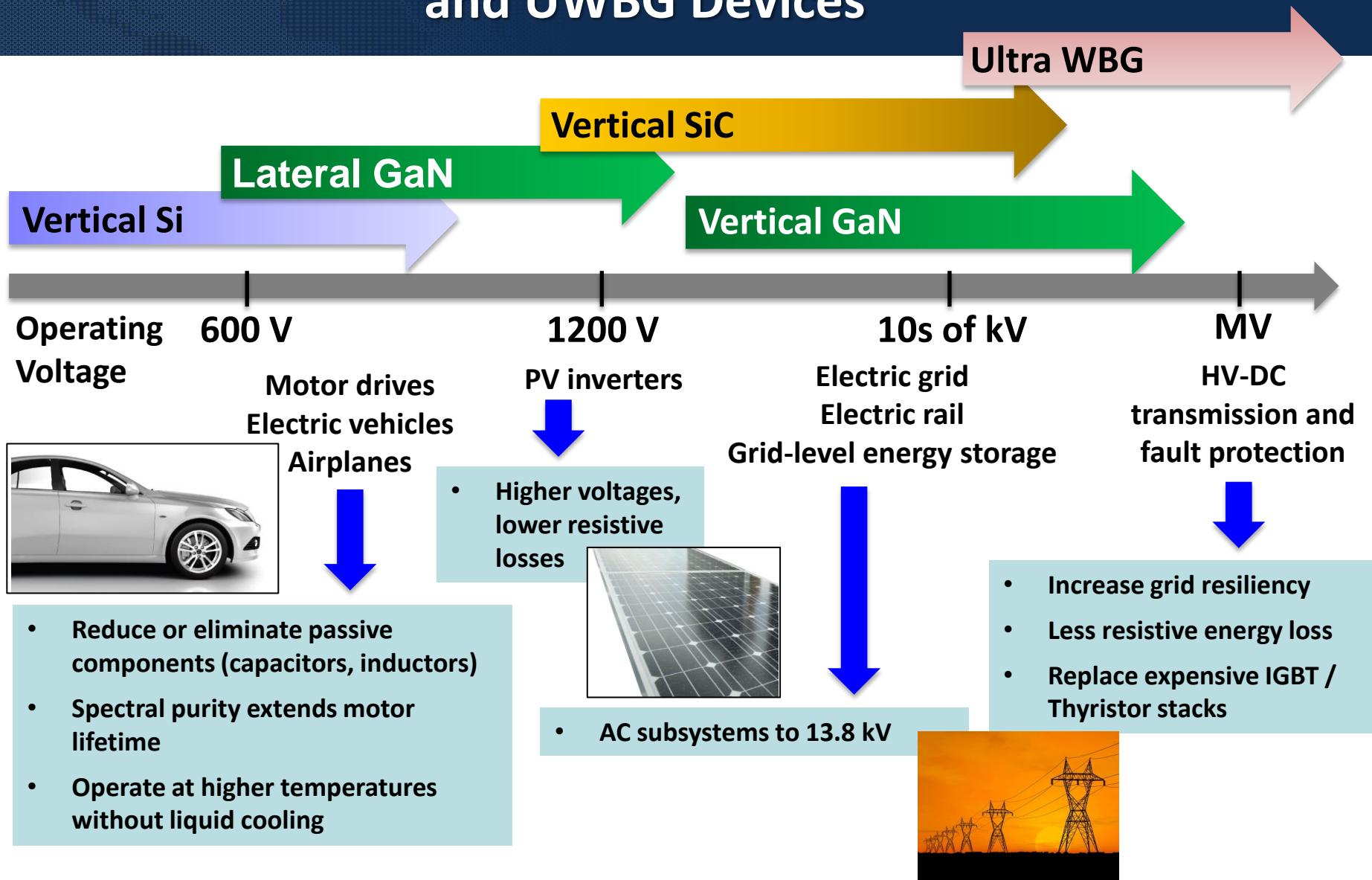


## HV double pulse test circuit

## HV current-voltage tracer

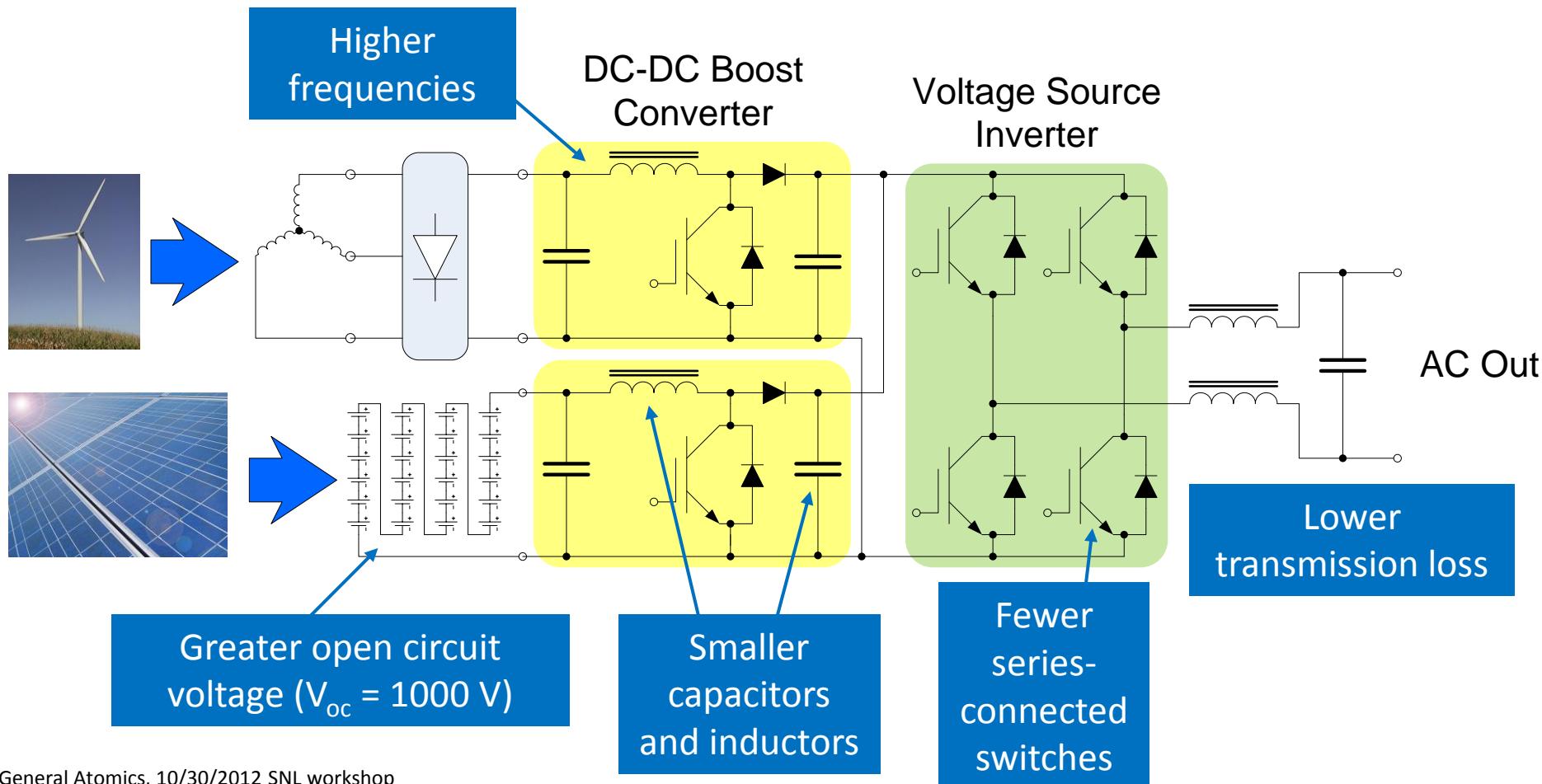


# Civilian Application Space for WBG and UWBG Devices



# 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



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



**USS Zumwalt**

**Higher degree of electrification  
desired in a SWaP-constrained  
environment**

## Electromagnetic Railgun



**USS Gerald R. Ford**



# Questions?

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**505-844-8285**  
**[rjkapla@sandia.gov](mailto:rjkapla@sandia.gov)**