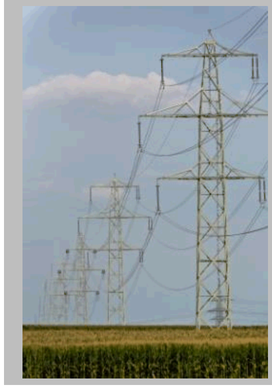
SAND2014-18881PE

*Exceptional service in the national interest*



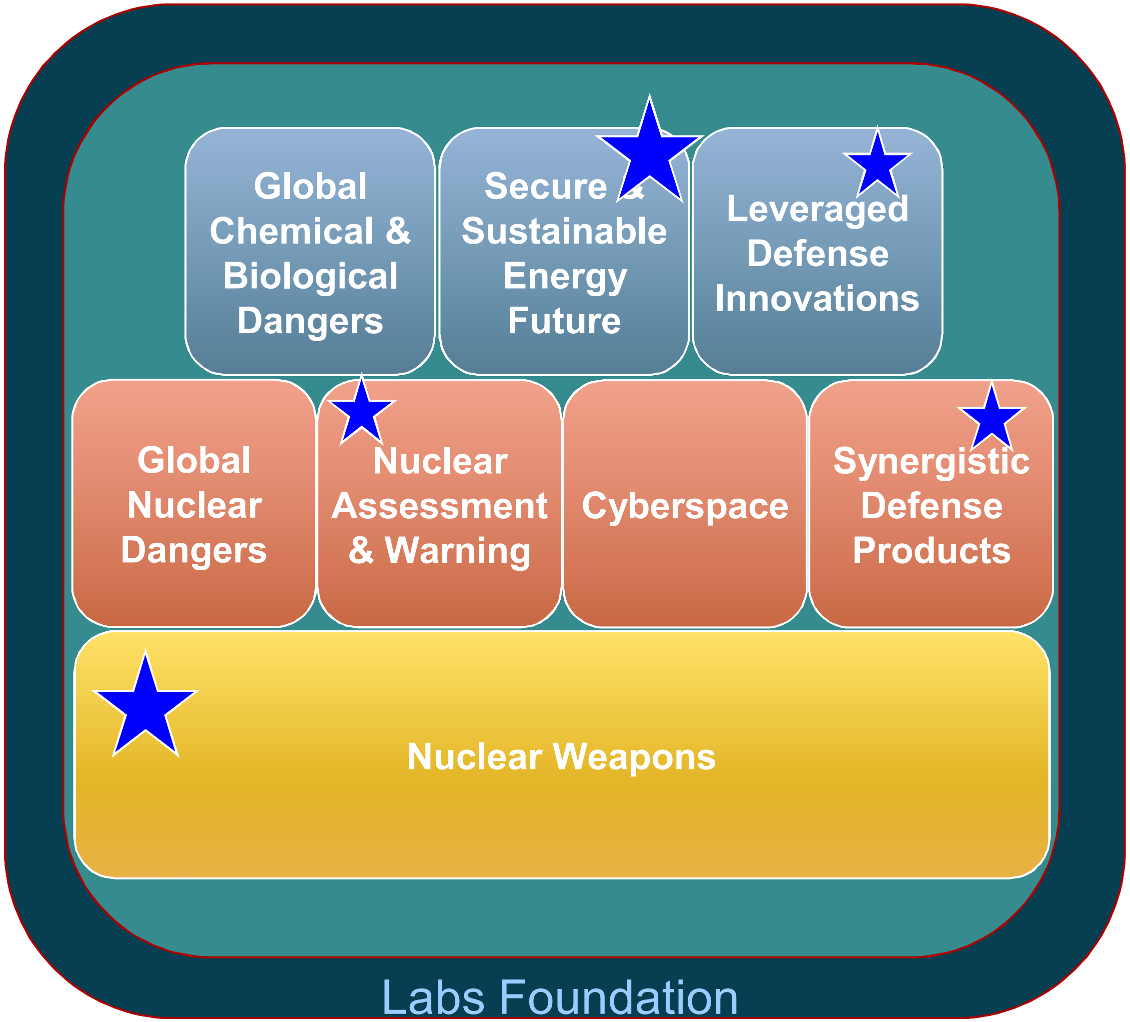
# Power on Demand (PoD) Research Challenge: An Informal Overview

**J. Charles Barbour, Director**

**Radiation & Electrical Sciences Center**

**Sandia National Laboratories, New Mexico, USA**

# Compact, lightweight, reliable Electrical Power is a crosscutting need of several Mission Areas



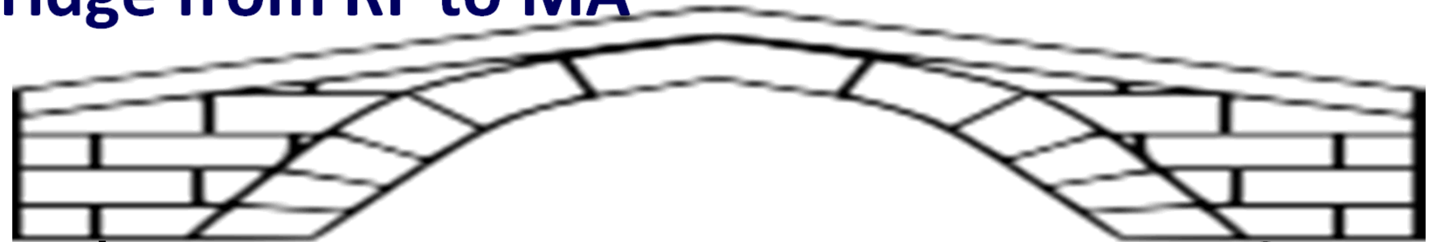
# Power on Demand: Vision and Goal

- **The need for power is ubiquitous.**

  *We will develop power systems with the smallest size, lightest weight and highest conformability, for the harshest environments*

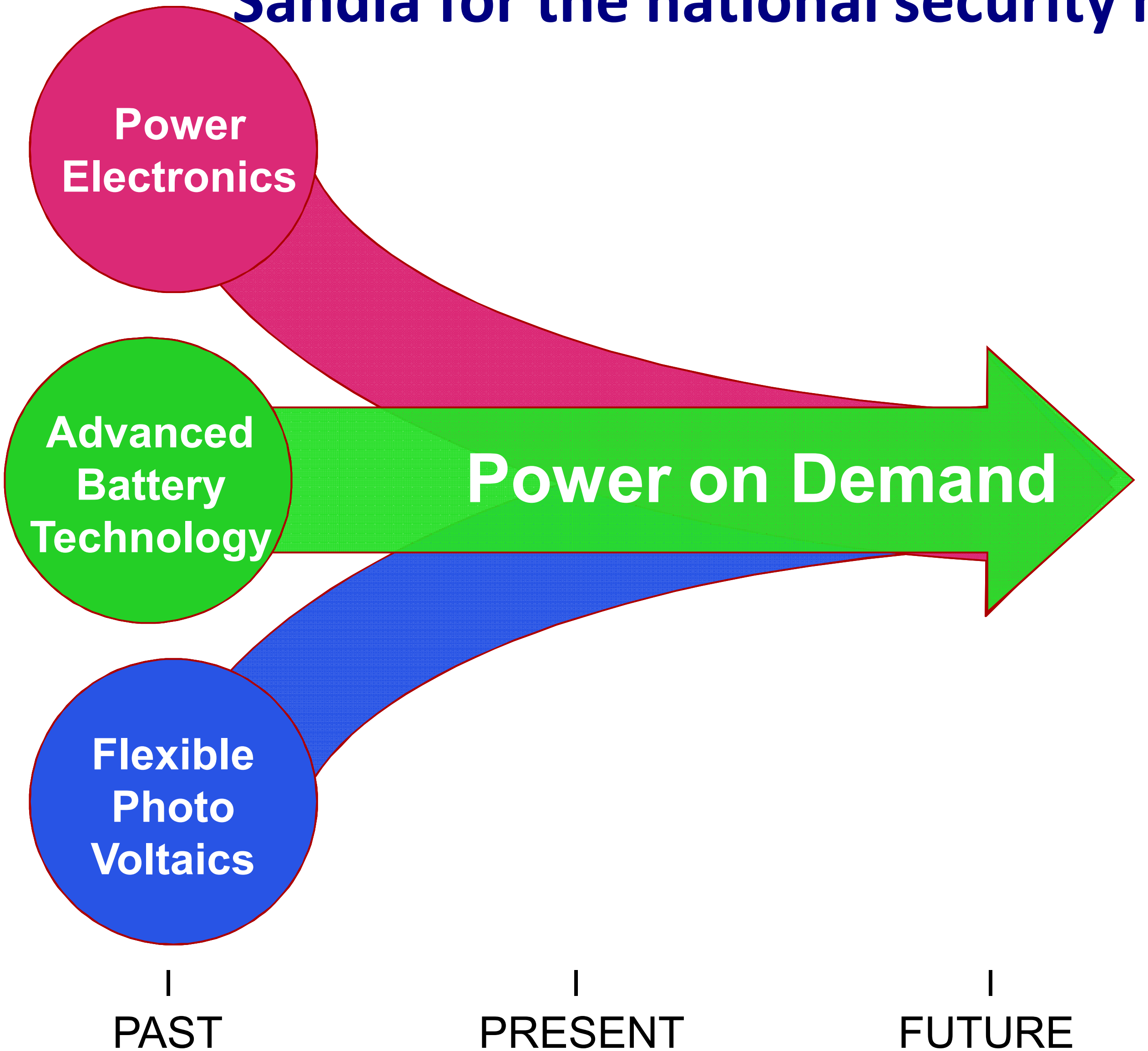
- **Focus on Electrical Energy**
- **Seek Impact on Mission Areas**
- **Power on Demand** will coordinate a portfolio of work to develop **innovative new technology capabilities** that enable electrically powered systems with differentiating SWaP characteristics:
  - **National security applications** (low, medium & high power)
  - **Civilian energy sector** (grid-scale conversion, storage, and transmission; electric vehicles; and building and industrial efficiency).

# PoD Bridge from RF to MA



| Research Foundations | Research Goals | Sandia Mission Area |
|---|---|---|
| **Material Science** | • High efficiency, ultra-light weight and compact electrical power systems<br>  • *Requires innovation across generation, storage, conversion technologies* | **Nuclear Weapons** |
| **Nanodevices & Microsystems** | • New devices and systems with enhanced lifetimes, reliability, and resilience, for both civilian and military applications<br>  • *Fundamental understanding for predictive reliability of power system components* | **Leveraged Defense Innovations** |
| **Radiation Effects and High Energy Density Science** | • Novel approaches for generating and harvesting power for long times in harsh environments (incl. radiation) | **Nuclear Assessments and Warning** |
| **Engineering Science** | | **Synergistic Defense Products** |
| | | **Secure and Sustainable Energy Future** |

# Integrated capabilities will differentiate Sandia for the national security missions




***Sandia will be the Lab that best understands how to deliver electrical power systems with differentiating SWaP characteristics and reliable performance in harsh environments***

# Three technical focus areas were chosen (in order)

1. ***Power electronics: wide bandgap semiconductor materials, devices, and power systems.***
   - Large gains in size, weight, and power efficiencies (SWaP) possible.
   - Materials are inherently rad-hard
   - Leverages SNL strengths in semiconductors and rad-hard components
2. ***Battery-based electrical energy storage – especially reliability.***
   - SWaP needed by both civilian and non-civilian applications.
   - Leverages SNL's lead NNSA role in batteries; SNL's lead partner role in JCESR
3. ***Microsystem-enabled photovoltaics (MEPV).***
   - Leverages results of MEPV Grand Challenge LDRD
   - MEPV cells superior in light weight and flexibility

# Target Device Classes / Demos

1. kV class device (5 kV target)
   - NW Application; E&C vehicle
   - Three-terminal, normally-off
   - $R_{on} < 2\ m\Omega \cdot cm^2$
   - < 100 ns switching
   - $J > 1\ kA/cm^2$
   - Establish physical foundation for high reliability and radiation resistance

2. Tens-of-kV class device (15 kV target)
   - NW Application; Energy grid
   - Two-terminal (simpler device for such high voltages)
   - $R_{on} < 20\ m\Omega \cdot cm^2$
   - $J > 2.5\ kA/cm^2$
   - Establish physical foundation for high reliability and radiation resistance

- 1200 V device can be used as a "standard" along the way to establish feasibility of materials and device architecture
  - NW Application
  - Reliability / radiation effects stepping stone and potential early system insertion

# Technical Development Flow

| | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| **Synergistic Applications**<br>*Demo Activity TBD–Business Development* | • Power distribution<br>• SWaP for Electrical Vehicle / PV Inverter | | • SWaP for Grid<br>• HV power electronics for Pulsed Power applications |
| | 1.2kV $Al_{0.3}Ga_{0.7}N$ HEMT | N-off $Al_{0.7}Ga_{0.3}N$ 5 kV HEMT | **Exemplar Demos**<br>• PoD demonstrator<br>Vertical 5kV $Al_{0.7}Ga_{0.3}N$ JFET *(path to 15 kV vertical 3-terminal)*<br>15kV $Al_{0.7}Ga_{0.3}N$ 15 kV PiN |
| **Device & System Proof-of-Concept Demo** | 1.2kV $Al_{0.3}Ga_{0.7}N$ Schottky<br>5kV $Al_{0.3}Ga_{0.7}N$ PiN<br>1.2kV $Al_{0.7}Ga_{0.3}N$ Schottky | 5kV $Al_{0.7}Ga_{0.3}N$ PiN | |
| **Novel Device Realization**<br>Gate Stack & Ohmic Contacts<br>Field Engineering<br>Substrate removal | Field Engineering for 1.2kV HEMT<br>Gate Stack for AlGaN HEMT<br>Ohmic Contacts for AlGaN | Field Engineering for 5kV HEMT | Field Termination for 15kV PiN<br>Substrate Removal (70% AlGaN) |
| **Fund. Physics of Rel.**<br>2DEG in Heterostructures<br>Radiation Resilience<br>Defect Structure and ID | 2DEG Formation - $Al_{0.3}Ga_{0.7}N$<br>DFT of defects in $Al_{0.3}Ga_{0.7}N$<br>Defects in $Al_{0.3}Ga_{0.7}N$ | 2DEG formation $Al_{0.7}Ga_{0.3}N$<br>Defects in $Al_{0.7}Ga_{0.3}N$<br>- correlate to DLOS, DFT | Baseline Reliability |
| **UWBG Material Synthesis**<br>Material Quality (xtal., elect.)<br>Epilayer Design<br>Doping Strategies | Thick, low-doped n-$Al_{0.3}Ga_{0.7}N$<br>Low TDD AlN on sapphire | p-doping in $Al_{0.7}Ga_{0.3}N$<br>10μm thick $Al_{0.7}Ga_{0.3}N$ | AlN/GaN superlattices<br>10μm thick BAlGaN |

# What are *Power Electronics*, and Why Do We Care?

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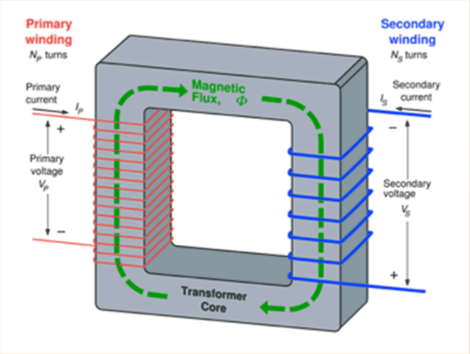
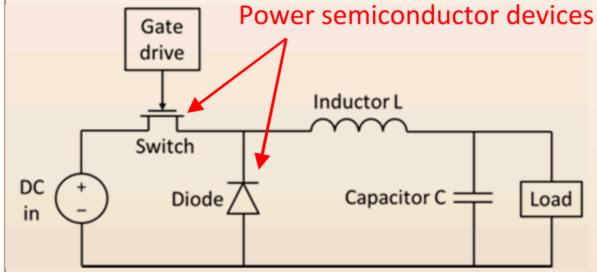
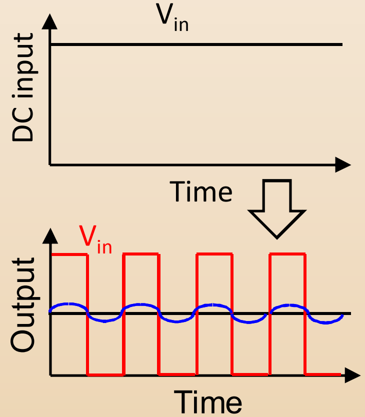
- ***Power electronics***: Application of solid-state electronics for routing, control, and conversion of electrical power

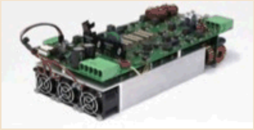
***Passive transformers (dumb)***




***Power Electronics – Active switching (smart)***



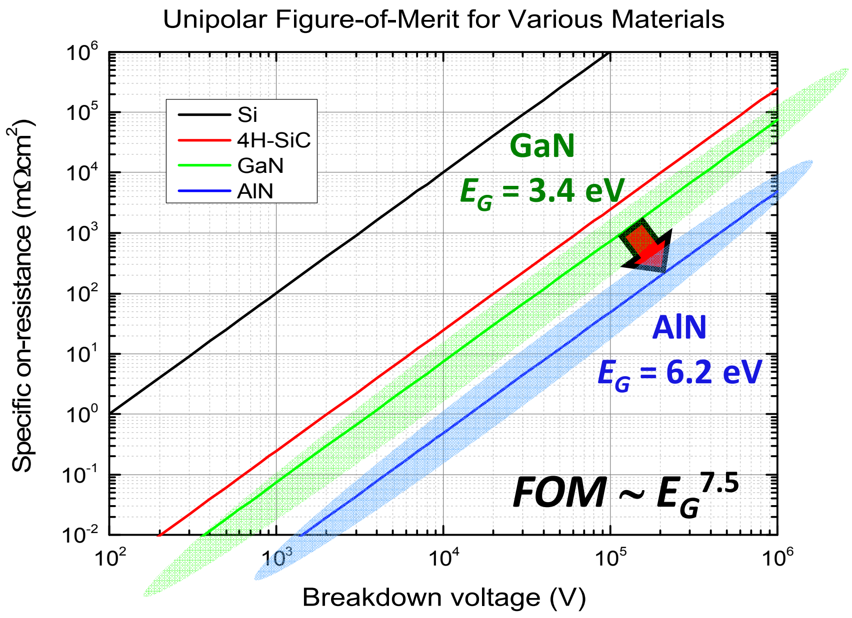
- **Current power electronics are limited by the properties of Silicon semiconductor devices**
- **New system capabilities are enabled by:**
  - **Higher switching frequency (enables better SWaP)**
  - **Lower power loss**
  - **Higher temperature operation**
  - **Radiation resistance**

➢ ***Motivation for (U)WBG semiconductors***

# UWBG materials for Rad-Hard Power Electronics

| Property | Si | GaAs | 4H-SiC (WBG) | GaN (WBG) | AlN (UWBG) |
|---|---|---|---|---|---|
| Bandgap (eV) | 1.1 | 1.4 | 3.3 | 3.4 | 6.2 |
| Critical Electric Field (MV/cm) | 0.3 | 0.4 | 2.0 | 3.3 | 11.7 |
| Saturated electron velocity ($10^7$ cm/s) | 1.0 | 1.0 | 2.0 | 2.5 | 1.4 |
| Thermal conductivity (W/cm·K) | 1.5 | 0.5 | 4.5 | 4.0 | 3.4 |
| Ionization energy (eV/e-h pair) | 3.6 | 4.8 | 8.7 | 10.3 | ? |

Decreasing TRL →




- **Greater breakdown voltage:** Fewer devices in series
- **Higher frequencies:** Smaller passive circuit components
- **Lower conduction and switching losses:** Higher efficiency
- **Higher operating temperature:** Less cooling, lower failure rate
- **Higher radiation resistance** (ionization and displacement damage)

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

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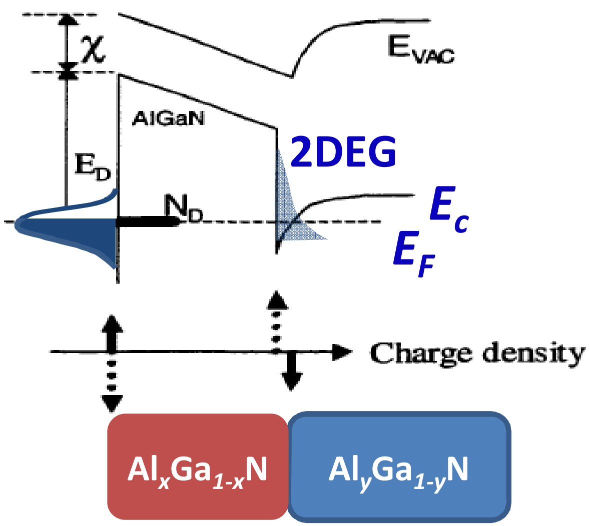
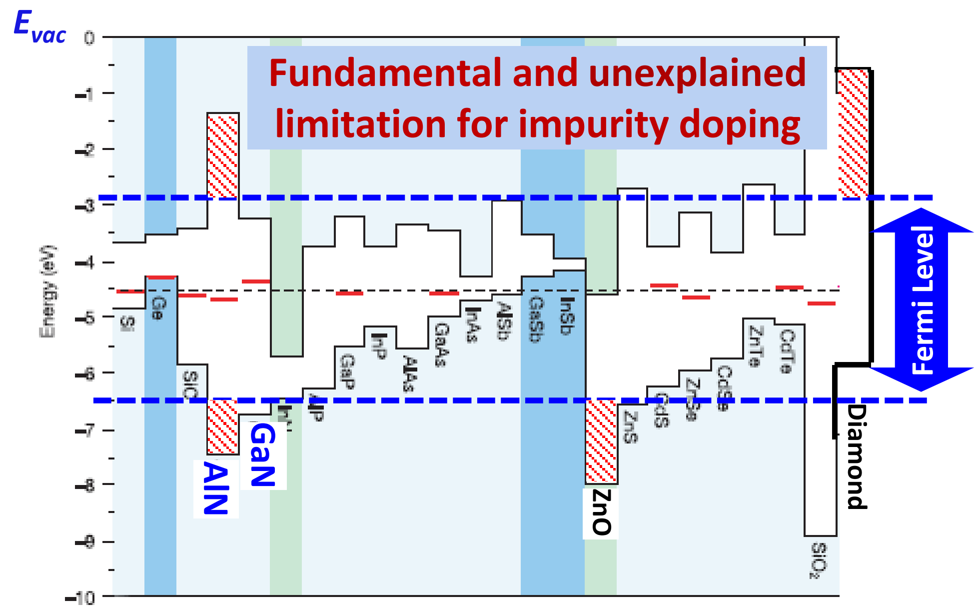
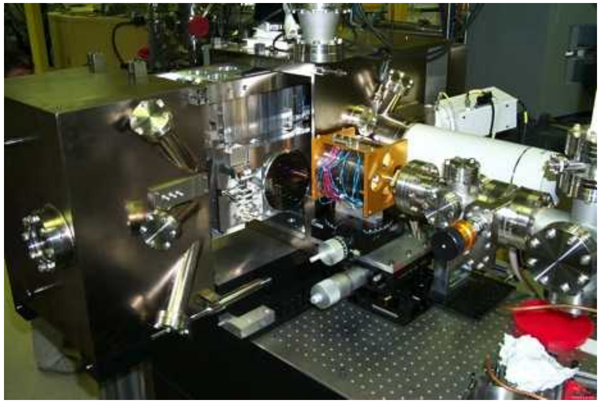
## Physics of 2DEG formation in UWBGs

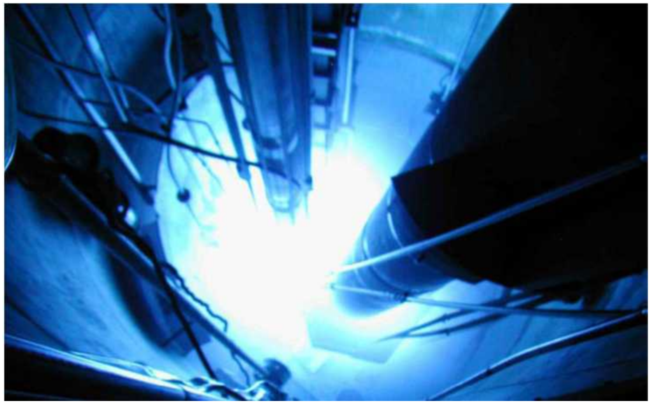



Chris G. Van de Walle* & J. Neugebauer†

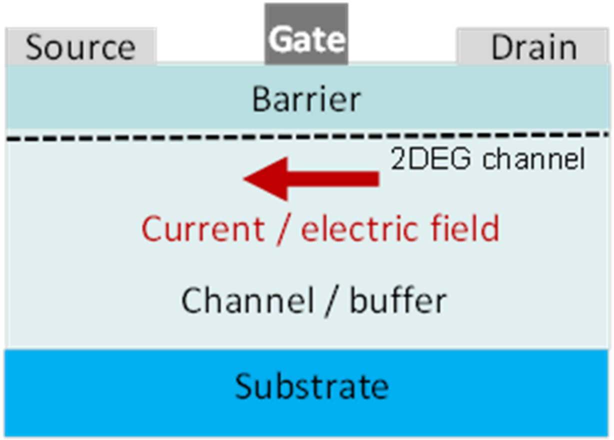
NATURE | VOL 423 | 5 JUNE 2003 |





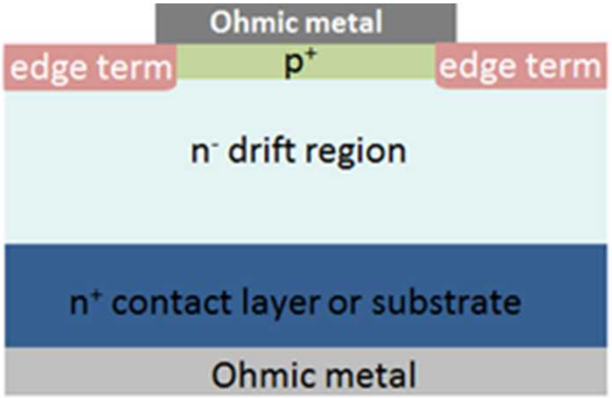
**Materials- and device-level effects from defects**

# Advanced Concepts, Design, and Fabrication for Novel Power Device Realization




***Lateral device***

- **Advanced gate stack engineering for normally-off operation**
- **Novel field plate designs for high breakdown voltage**




***Vertical device***

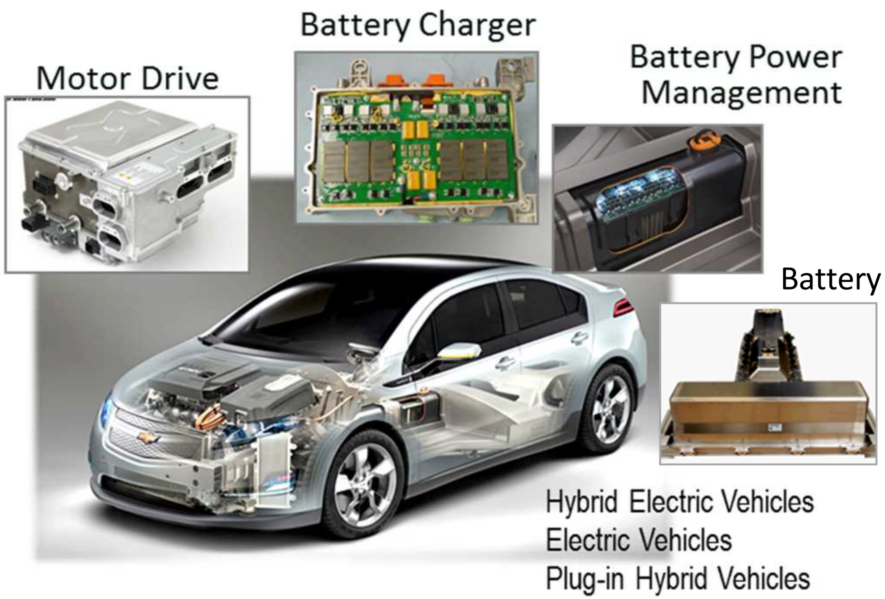
- **Removal of insulating substrates for true UWBG vertical devices**
- **Fundamental physics of breakdown and carrier transport**

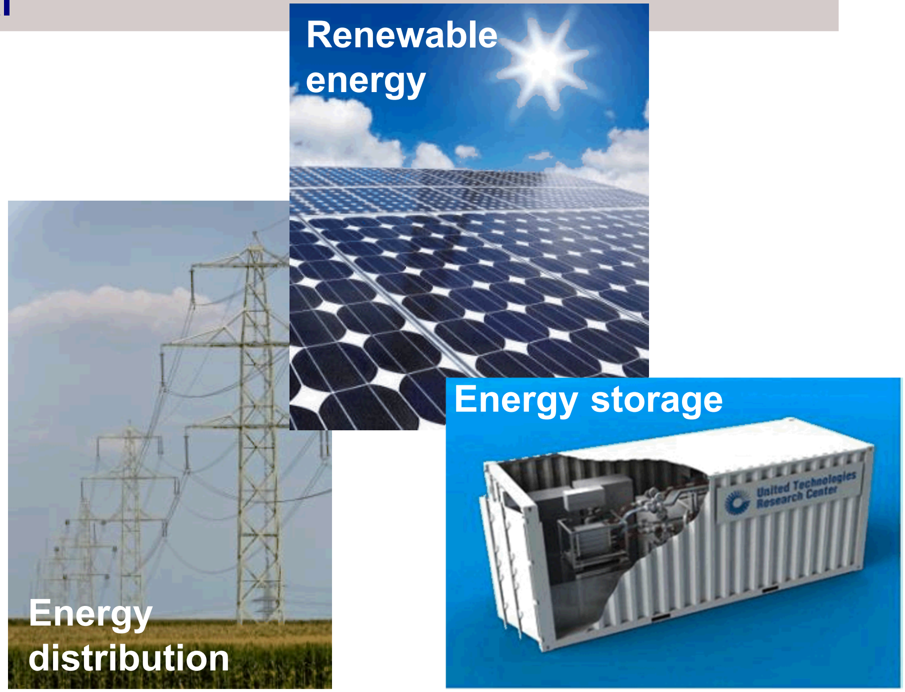
# Scope: Sample Research Questions

- **Power Electronics (Materials)**
  - What influences conductivity and defect structure of UWBG AlGaN and how can this understanding be used to generate device quality materials? What 2D charge densities can be achieved?
  - What are the dominant atomic-scale failure mechanisms of power devices? Why does GaN break down before its calculated avalanche breakdown field?
  - What are the defects introduced in relevant radiation environments (x-ray, $\gamma$, protons, electrons, neutrons, heavy ions) and how do they affect the material (displacement vs. ionization); what is important for different device types?

# Mission Needs: Civilian Energy

| Mission Area | Examples of Specific Areas of Interest and Impact |
|---|---|
| Secure and Sustainable Energy Future (Energy and Climate) | • **Next-generation grid** (efficiency & intelligence; long & short term storage)<br>• **Transportation sector** (vehicle electrification)<br>• **Solar PV, PV Inverters and Wind Inverters** (clean electricity; key enabling technology for increasing grid renewable generation)<br>• **Building and Industrial efficiency** (variable speed electrical motors for HVAC, elevators, industry)<br>• **Small power supplies and appliances** – computers, solid-state lighting power drivers, appliances<br>• **Electric rail, aeronautical** |



# Energy and Climate Mission Impact

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**Traction Drive**

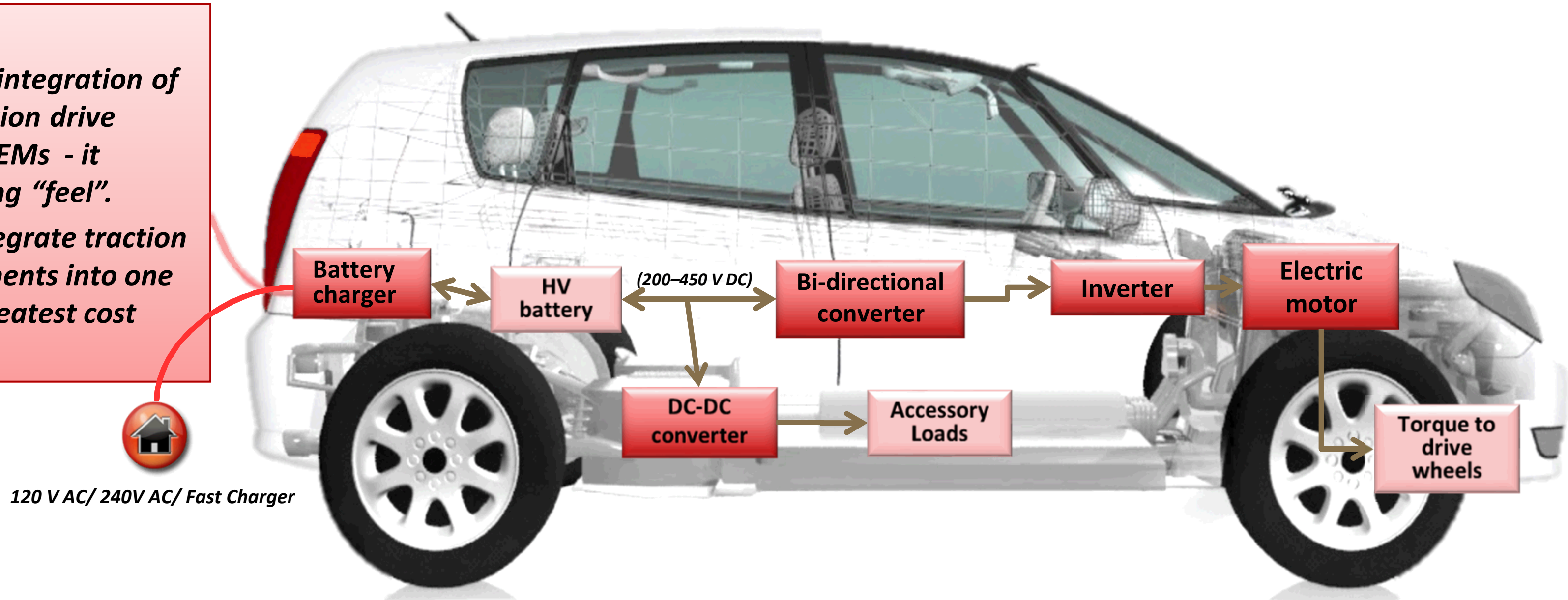
- ***Battery charger*** – Necessary for plug-in hybrids and electric vehicles
- ***Bi-directional boost converter*** – Steps up the battery voltage when the traction system requires a higher operating voltage than the battery can supply
- ***Electric motor*** – Converts electrical to mechanical power for the wheels
- ***Inverter*** – Converts direct current (DC) to alternating current (AC) for the electric motor

**Power Management**

- ***DC-DC converter*** – Steps down the high battery voltage to power ancillary systems such as lighting, brake assist, and power steering, and accessories such as air conditioning and infotainment systems.

***Emphasis:***

- ***Design and integration of electric traction drive critical to OEMs - it affects driving "feel".***
- ***Goal is to integrate traction drive components into one system for greatest cost efficiency.***



# WBG Power Electronics: SWaP for Secure and Sustainable Energy Future

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## *Lighting*

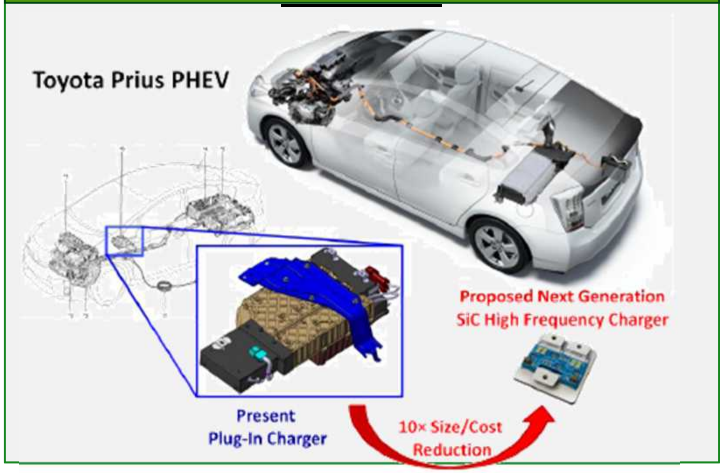
Existing 25 W AC-DC SSL Driver

EMI Filter Power Stage:

130 mm x 45 mm x 25 mm

*300X reduction in power stage volume*

## *Automotive*

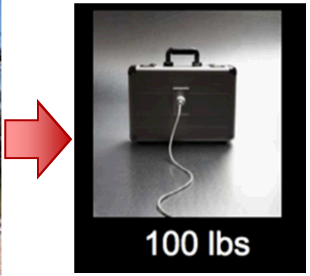




**SiC system is 10% the volume and weight of Si for equivalent capability (10 kV, 100 A)**

## *Power Grid*

*8000 lbs, 60 Hz Distribution Transformer*




*Silicon Carbide IGBT; 15 kV, 100 A; 50 kHz from Cree Inc.*

*Potentially 100 lbs Transformer*

**80% of grid power expected to flow through PE by 2030**

**UWBGs will offer an *additional* 10× SWaP improvement compared to SOA SiC and GaN, as well as Ultra-High-Voltage (potentially 100's of kV)**

# Energy Storage Safety/Reliability Issues Have Impact Across Multiple Application Sectors

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2006 Sony/Dell battery recall 4.1 million batteries

2008 Navy, $400M Advanced Seal Delivery Sub, Honolulu

2010 FedEx Cargo Plane Fire, Dubai

2011 NGK Na/S Battery Explosion, Japan (two weeks to extinguish blaze)

2011 Chevy Volt Latent Battery Fire at DOT/NHTSA Test Facility

2011 Beacon Power Flywheel Failure

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

2012 GM Test Facility Explosion, Warren, MI

2013 Boeing Dreamliner Battery Fires, FAA Grounds Fleet

2013 Nissan Leaf Battery Degradation

2013 Storage Battery Fire, The Landing Mall, Port Angeles, (reignited one week after being “extinguished”)

# Current State of Battery Safety Needs

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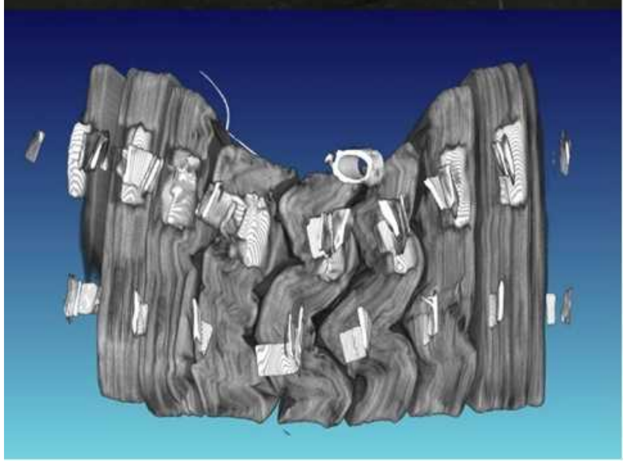
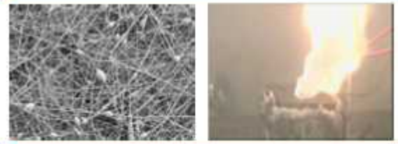


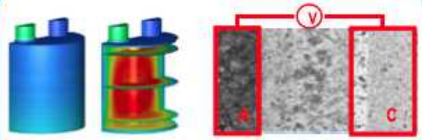


**Materials R&D**

- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials

**Testing**

- Electrical, thermal, mechanical abuse testing
- Failure propagation testing on batteries/systems
- Large scale thermal and fire testing (TTC)
- Development for DOE Vehicle Technologies and USABC



**Simulations and Modeling**

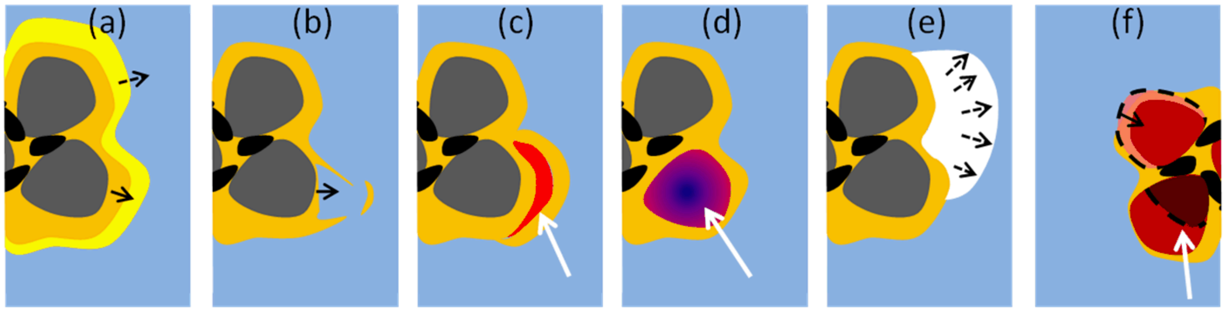
- Multi-scale models for understanding thermal runaway
- Validating vehicle crash and failure propagation models
- Fire Dynamic Simulations (FDS) to predict the size, scope, and consequences of battery fires

**Procedures, Policy, and Regulation**

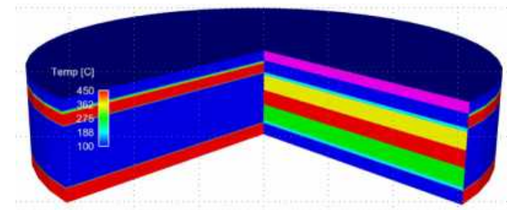
- USABC FreedomCAR Abuse Testing Manual
- SAE J2464, UL1642
- Testing programs with NHTSA/DOT to influence policies and requirements

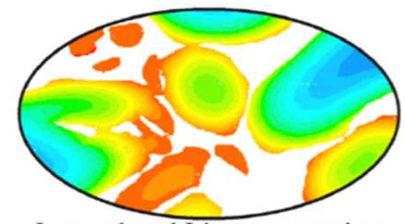

*Predictive tools, informed by scientific study and validated against complex test conditions, are needed to develop next generation material, reduce build/test design cycles, scale testing to larger systems, respond to critical safety incidents, and inform policy and regulatory procedures.*

# How Can We Bridge Fundamental Research to Mission Area Reliability Challenges?

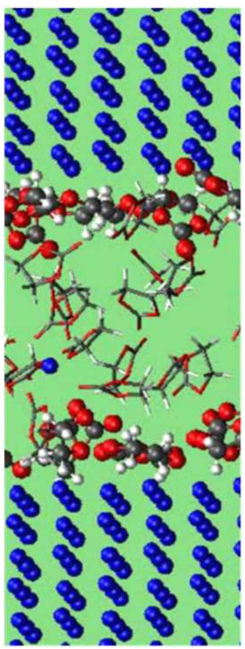


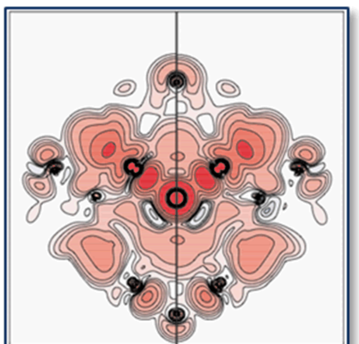

Potential degradation mechanisms (a) SEI growth (b) SEI delamination (c) Li plating (d) active particle stranding, (e) blocking of electrolyte channels by gas bubbles, and (f) active particle dissolution or phase change

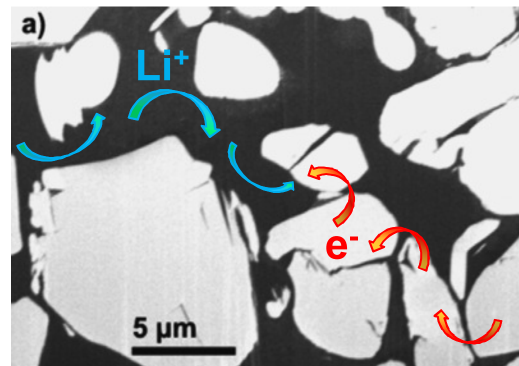


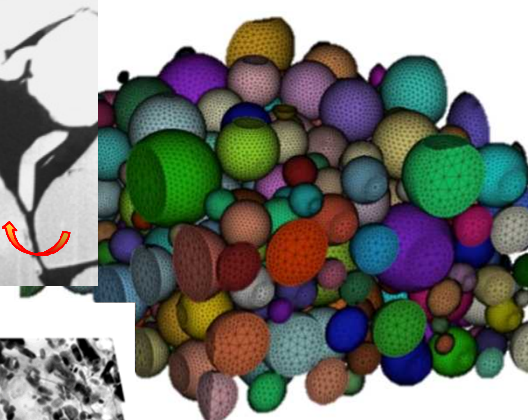



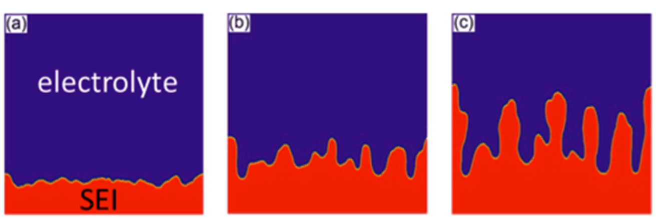
Intercalated Li concentration

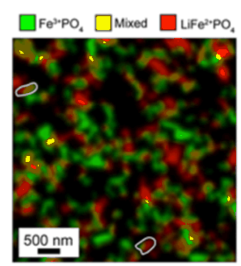




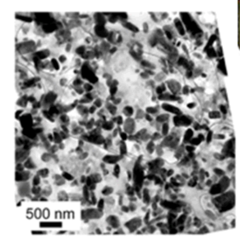




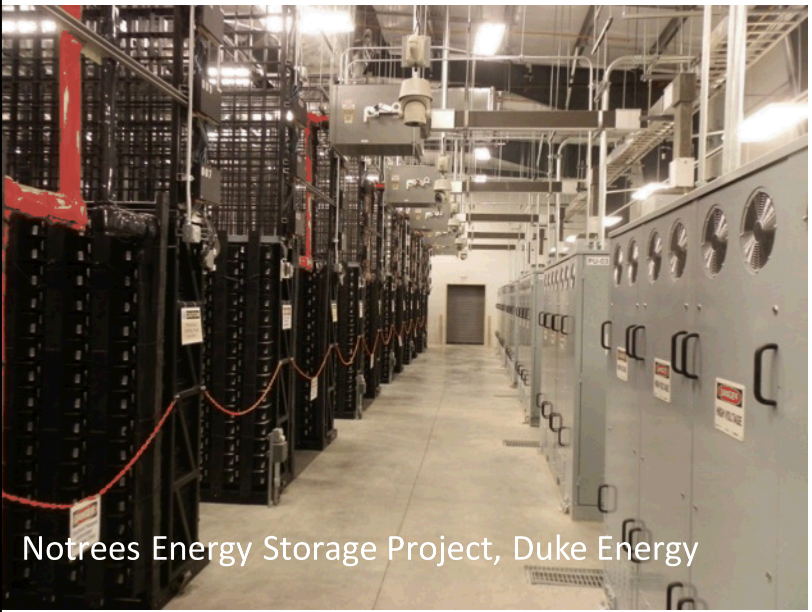

51.3 % SoC




Sullivan, Leung, Muller, Frischknecht, Hewson, Moffat, Grillet, El Gabaly, Roberts, Schunk, Bolintineanu, Lechman, Wiedemann, Kee

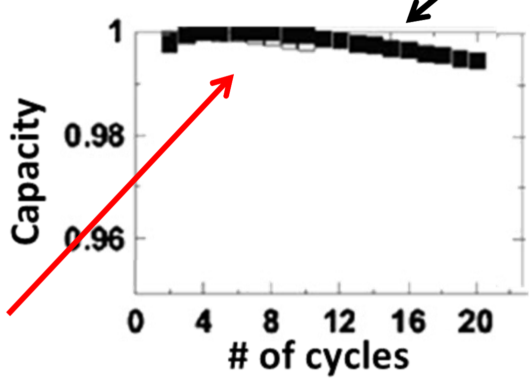
# Energy Storage: How big can we go?

- **Large scale storage challenges**
  - Safety
    - Intrinsic (battery is the cause)
    - Extrinsic (external cause)
  - Reliability
    - Failure modes
    - Lifetime (e.g. degradation)



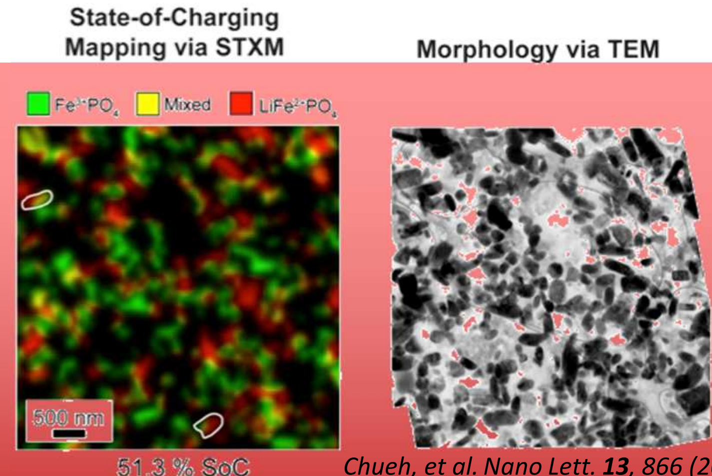
Notrees Energy Storage Project, Duke Energy

*http://evnewsreport.com/category/ev-star-of-the-week/*




*a little bit is lost every cycle*

*Smith et al, Electrochem. Solid State Lett. 13, A177 (2010).*



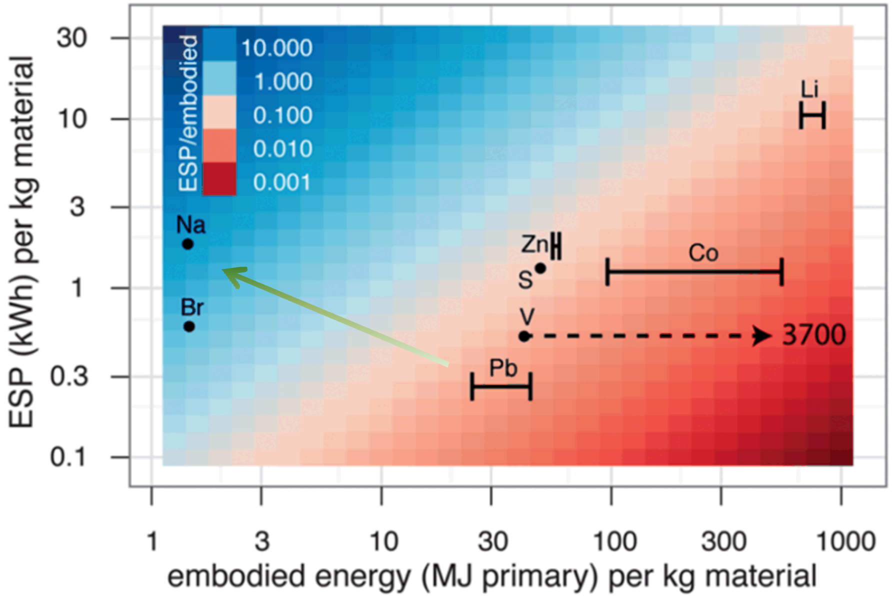

*Chueh, et al. Nano Lett.* ***13****, 866 (2013).*

Lithiation controlled by surface nucleation, not solid state diffusion

# Accelerating Distributed Sodium Battery Storage

- SOA: Na-S battery storage
  - Utility-scale NaS units support load shifting
  - Example: AEP 1.2 MW/6 hour peak shaving
  - Issues limiting adoption:
    - high operation temperature (> 300°C )
    - fragile β”-$Al_2O_3$ Na electrolyte membrane
    - high storage cost
    - safety issues


- Distributed storage need: low cost, safe energy storage batteries




C. J. Barnhart and S. M. Benson, Energy and Env. Sci., 6, 1083, (2013)

Stationary energy storage cost predictions:

Li-ion $ 650/MW-h* — *2013 DOE-EPRI Energy Storage Handbook

V redox $ 420/MWh*

Na-S $ 260/MW-h*

Pb-acid $ 220/MW-h* (present standard)

DOE goal $<100/MW-h*

Na-I, Na-Br $ 60/MW-h (deployed cost ~2X materials cost)

Sandia is developing sodium-based batteries under DOE-OE funds for grid energy storage

# Scope: Sample Research Questions cont.

- **Battery Safety and Reliability**
  - How can we translate a foundational understanding of degradation and failure mechanisms into a means to prevent them or minimize their impacts?
  - Can the scientific insights we gain be used to design inherently safe and reliable energy storage systems?
  - What scaling methods can be developed to extend understanding of failure modes and mechanisms at testable scales to very large format energy storage systems?
  - What ingenious new form factors and mechanisms for micro-power can be achieved?

# Scope: Sample Research Questions cont.

- **Flexible Photovoltaics**
  - What new semiconductor material families can enable a wider spectral range of peak efficiency wavelengths while maintaining crystal lattice matching?
  - How can plasmonic and photonic crystal effects be leveraged to enable ultra-wide spectrum PV?
  - What innovations in concentration optics and device design or fabrication will decrease the balance of system cost in weight and size?
  - Can power electronics and storage be integrated with flexible PV for lighter weight, higher configurability, and agility?  What limits the power efficiency and reliability in the design of this integrated power system?

# Why Sandia?

- Sandia is branded as a leader in **compound semiconductor materials and device research** for national security needs - **DOE/NNSA mission lead in electronics**
- Sandia is a recognized leader in **battery materials and device research** with a focus on understanding battery performance and reliability in multiple environments - Lead lab in battery safety, reliability, and abuse testing
- Expertise in power systems (circuits, modules, networks)
- We have unique facilities in that are aligned with national security mission needs - **MESA, BATLAB, DETL, SSLS EFRC, CINT**, etc
- World class, multi-disciplinary research teams with a deep understanding of how our **materials and device research** can advance the missions
- Partnerships: Strong relationships with select labs, academia and industry
- ***Highly relevant historical expertise and ongoing research programs***

# Scope

## *Emphasis on Materials Science is deeply embedded in the Research Areas*

### Example Research Areas

- **Power Electronics**
  - **Ultra WBG Materials**
  - Novel power device architectures
  - Materials Reliability and Defect Physics
- **PV & Power Generation**
  - Plasmonic & Photonic crystal effects
  - Materials growth/processing
- **Battery Reliability Science**
  - Atomic-scale scientific understanding of failure mechanisms
  - Validated predictive models
  - Reliability of novel battery chemistries (e.g. Na-I, Na-Br)

### Technology Advances

- High reliability **power modules** at 10X – 100X smaller weight and power
- Low-cost, reliable **grid-scale power converters**
- **Rad hard power bus**
- Integrated science-based safety and reliability
- **Predictive design capability** for batteries
- Inherently safe and reliable **battery systems**
- Leveraging of key energy storage competencies for **mission areas**