# ARPA-E's Power Electronics Portfolio
## Materials to Applications

Olga Spahn, Program Director (olga.spahn@hq.doe.gov)

August 2, 2023

# Evolving Grid - Needs Better Technologies

- **Aging grid**


- **Changing weather**


- **Changing threat patterns**


- **Changing usage patterns**


- **Changing generation patterns**


**DER and industry electrification are transforming the grid**

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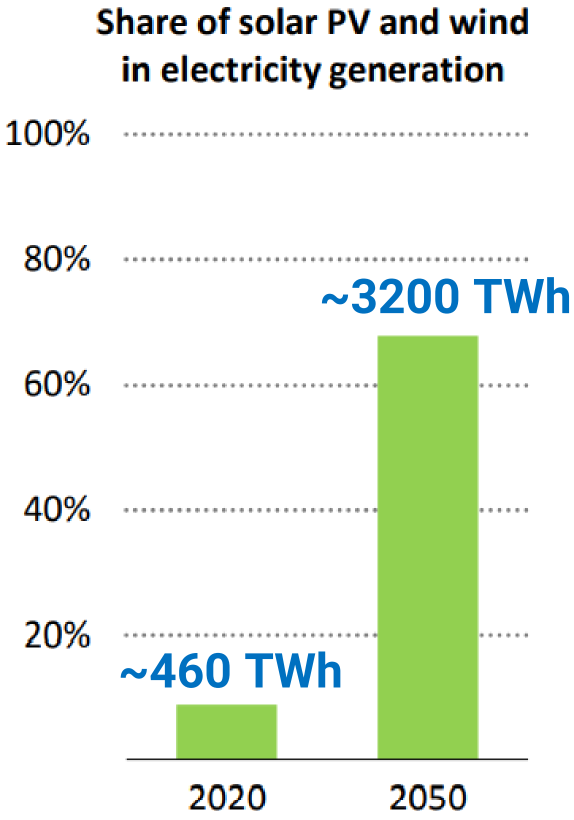
# Impact: Net Zero by 2050 Requires More DER Integration

- Share of electrified final power consumption to grow from 20% to 50% - electrification is driving everything
- Renewables key to reducing emissions
- **More and better power electronic will enable greater DER penetration**

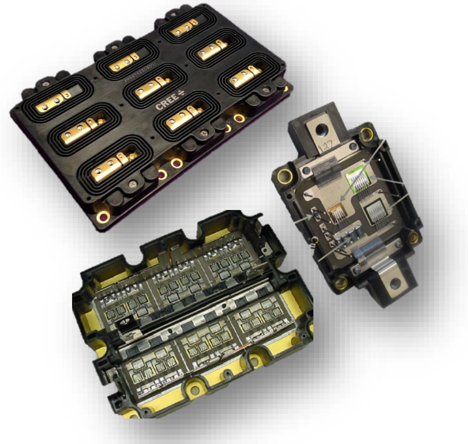




**~10x** increase in power electronics conversion required **in the next 25 years** just to support the primary source increase (generation to grid connection)



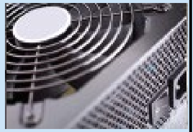
Net Zero by 2050 – A Roadmap for the Global Energy Sector, International Energy Agency - https://www.iea.org/reports/net-zero-by-2050

# Power Electronics Are a Key Enabler



- "Universal adapters" for grid to function like a standard bus allowing generic connections
  - Continuously controlled bidirectional power flow
  - Decoupled dynamics between loads, generators and the grid
  - Independent regulation of voltage and frequency at each side
  - Intrinsic protection, faults actively limited to a nominal value or interrupted
  - No thermo-mechanical switchgear
  - Low-frequency transformer-less voltage step-up / step-down

# Impact: Power Conversion Opportunities for Energy Efficiency

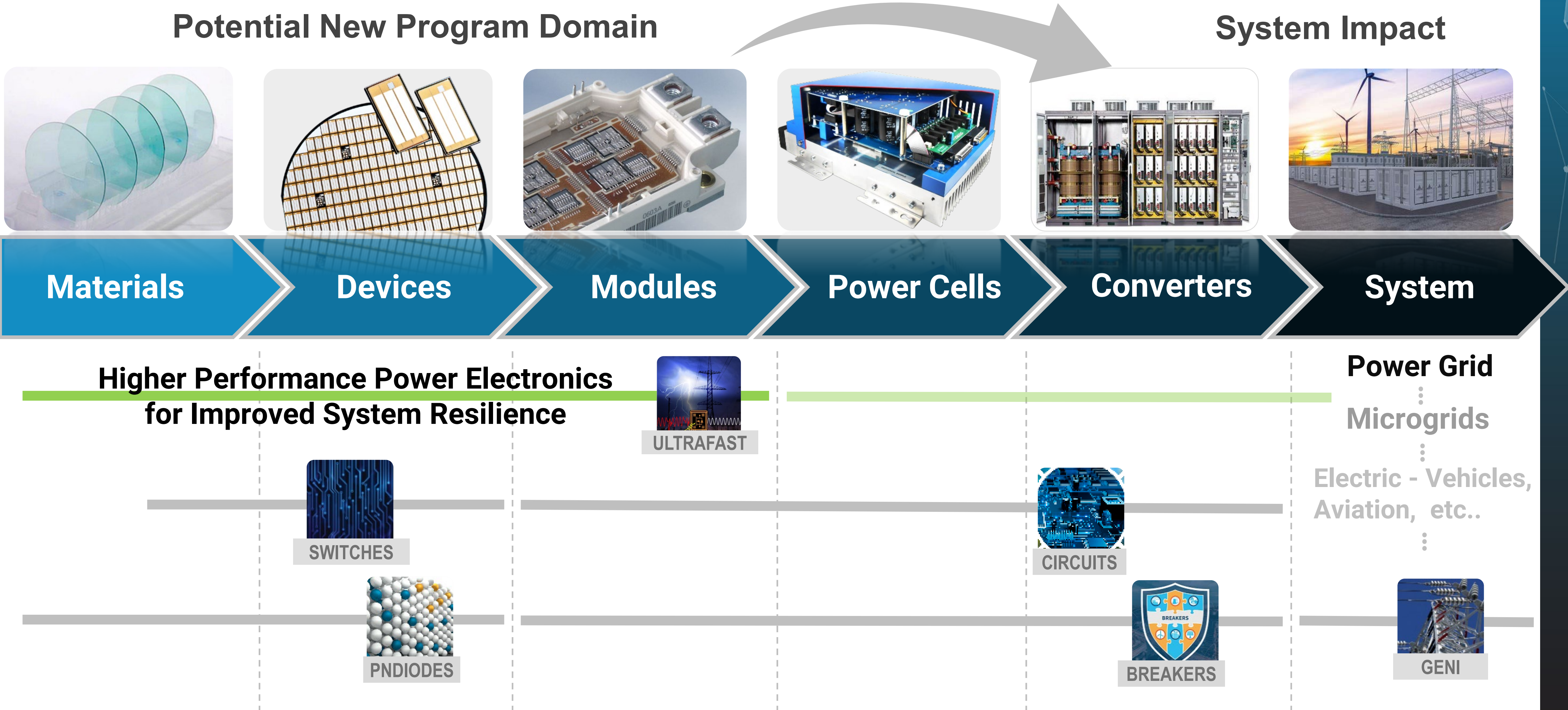
| | UPSs | High-End Power Supplies, Servers, etc | Hybrid Electric Vehicles | Solar Panel Inverters | Industrial Motors and Drives | Wind Turbines | Rail Traction, Ships | Grid Systems (FACTS, HVDC) |
|---|---|---|---|---|---|---|---|---|
| |  |  |  |  |  |  |  |  |
| Peak Currents | 2-100A | 0.5-10A | 50-200A | 75A | 3-100A | >150A | >200A | 1-10kA |
| Rated Voltage | 600-1200V | 600V | 650-2000V | 600-1200V | 600-1200V | 690V -> 3-4kV | >5kV | 10-100kV |

**Additional Opportunities** **Grid**

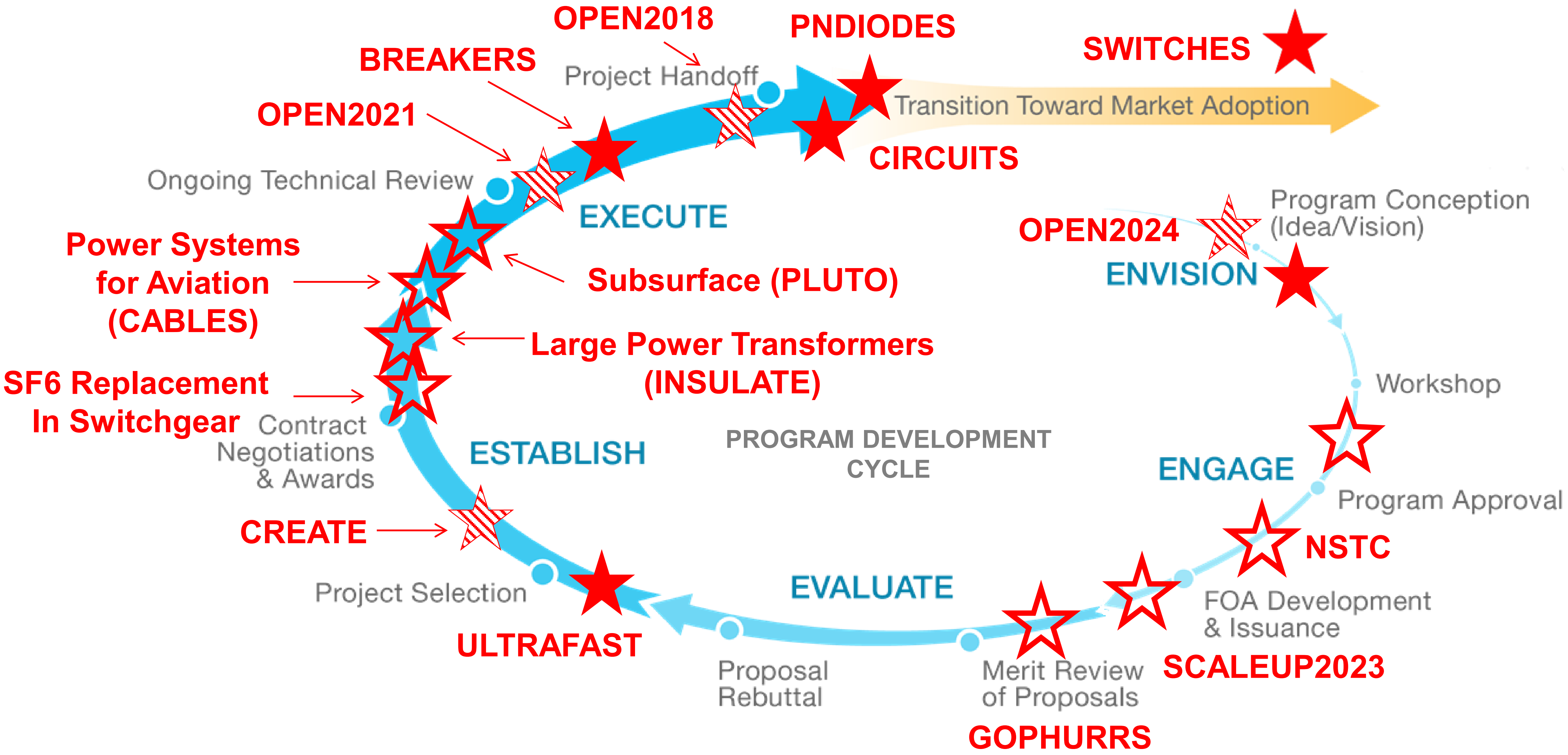
- **Electricity Usage**
  - 40% energy used 1st converted to electricity
  - Will grow to 80 % with electric and plug-in cars and other electrification
- **Electricity Use in Various Sectors**
  - Lighting (12%)
  - Motors (50%)
  - HVAC (16%)
  - IT (14%)
- **Sustainability and Energy Security**
  - Conversion efficiency
  - Generate from Renewable Sources
  - Resilient and Flexible Grid

**POWER ELECTRONICS is KEY in more than grid (80% of electricity will flow through power electronic converters by 2030)**

# Power Electronics Specific Focused Programs



# Current and Recent Power Electronics and Grid related programs

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# SWITCHES

Launched by Timothy Heidel
Program Director: Isik C. Kizilyalli

## Strategies for Wide-bandgap, Inexpensive Transistors for Controlling High Efficiency Systems


**Enable the development of high voltage (1200 V+), high current (100A+), wide-bandgap power semiconductor devices that have the potential for functional cost parity ($/A) with Si power transistors.**

PROJECTS

- High current density vertical GaN transistors (5) ← **Most transformative potential**
- Large area, low-cost bulk GaN substrates (6)
- Low cost, foundry-based, SiC device fabrication (1)
- Proof-of-concept diamond power semiconductor devices (2)

| | |
|---|---|
| Discrete Device Price | ≤ $0.10 /A |
| Breakdown Voltage | ≥ 1200 V |
| Continuous Drain Current | ≥ 100 A |
| Operating Junction Temp. | -55 to 150 °C |
| $I_{ON}$/ $I_{OFF}$ Ratio | > $10^6$ |

| | |
|---|---|
| Vth (not app. to diodes) | > 2 V @ $I_D$ = 5 mA |
| Dynamic Performance | Hard switched boost (PFC) f ≥ 40 kHz, 800 V, 50 A. |
| Specific $R_{DSON}$ | < 3 mΩ*cm$^2$ @ $V_{GS}$ = 15 V |
| Switching Loss $E_{ON}$+$E_{OFF}$ | < 0.5 mJ @ 800 V and 50 A |

**SWITCHES Technical Targets For High Performance and Market Viability**

# PNDIODES

Program Director: Isik C. Kizilyalli

## Power Nitride Doping Innovation Offers Devices Enabling SWITCHES

**2017, $17.4 Million**
**10 projects**

- **A mechanistic understanding of selective area doping in the III-Nitrides material system**
- **Leading to the demonstration of arbitrarily placed, reliable, contactable, and generally useable p-n junction regions that enable high-performance and reliable vertical power electronic semiconductor devices.**

PROJECTS

- Patterned etch and regrowth technologies (3)
- Ion implantation and innovative activation annealing technologies (3)
- Neutron transmutation doping for extremely uniform n-type GaN wafers (1)
- Expanded the Program to include Mg diffusion (1) and advanced characterization

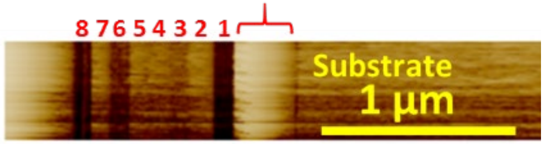
| | |
|---|---|
| Breakdown voltage | ≥ 1200 V |
| Leakage current | ≤ $10^{-9}$ A @ 600 V |
| Turn-on voltage | ~ 3.0 V |
| $I_{ON}$/ $I_{OFF}$ Ratio | > $10^{10}$ |

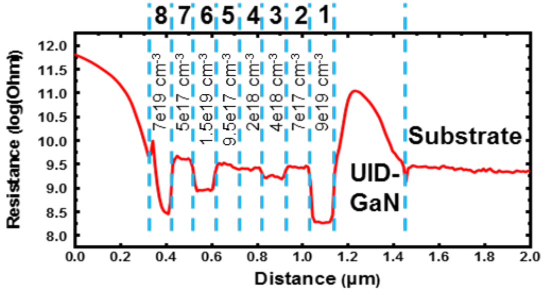
| | |
|---|---|
| Specific $R_{DSON}$ | < 3 mΩ*$cm^2$ |
| Avalanche capability | No parametric shift after repetitive avalanche testing |
| Surge capability | > 20 A surge capability for 10 μs pulse at 25˚ C |

**PNDIODES Program Specifications**

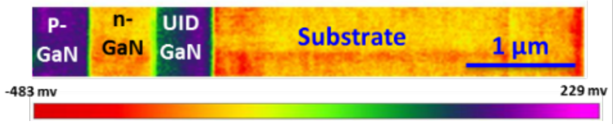
# Some Highlights from the PNDIODES Program

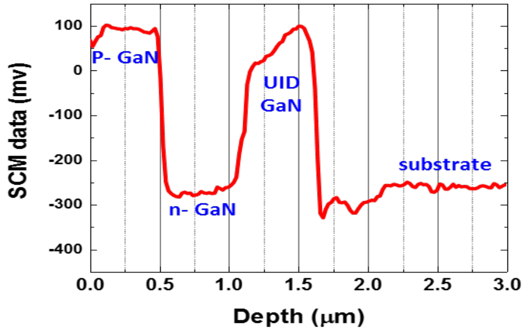
### Scanning Spreading Resistance Microscopy



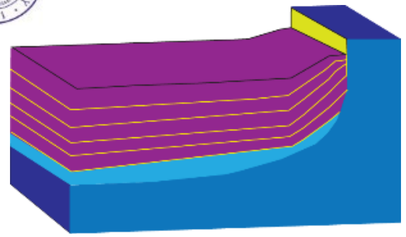



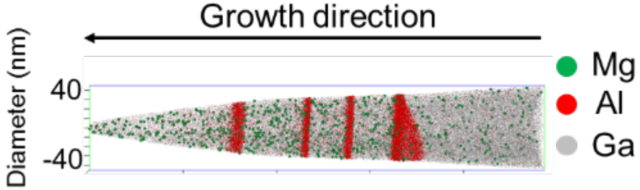

### Scanning Capacitance Microscopy

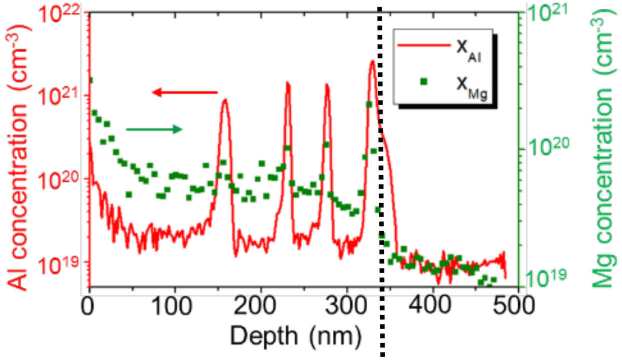


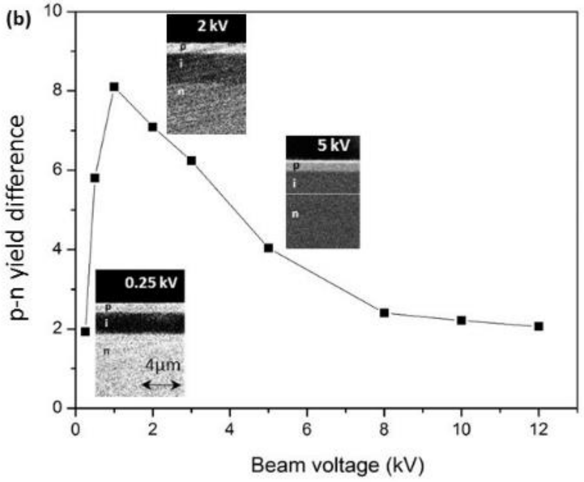

### Atom Probe Tomography



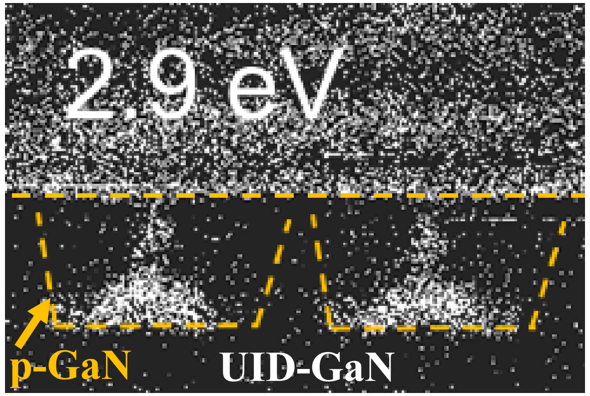


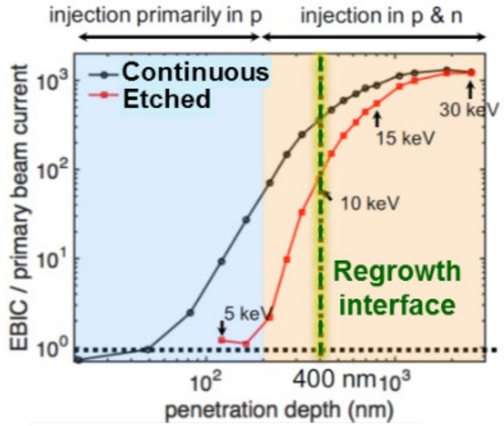

### Secondary Electrons

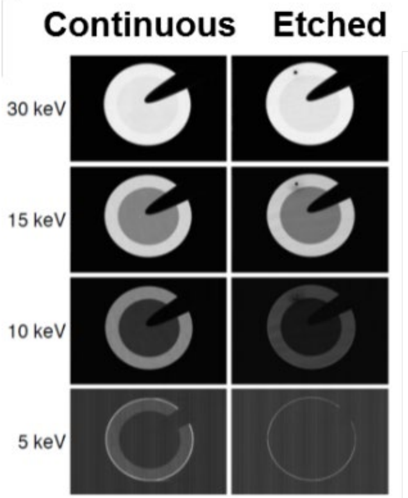



### Cathodoluminescence




### Depth-resolved defect profiling with Electron Beam-Induced Current




**Powerful Spatial Characterization Techniques for Selective Area Doping**

# CIRCUITS

Program Director: Isik C. Kizilyalli

## Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors


**Use advanced circuit topologies and fundamentally higher performing WBG semiconductor materials to realize efficiency gains both directly and indirectly in electric power conversion**

PROJECTS

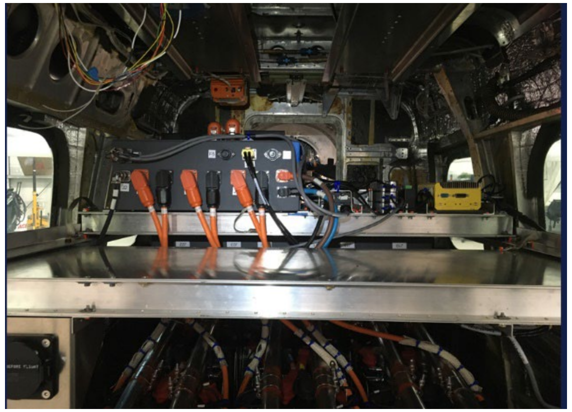
- Efficient DC/DC, DC/AC, & AC/DC converters (≥10 kW, 97.5%)
- Small size, low weight, reliable – Power Density > 150 W/inch$^3$
- Major contributions in power supplies, data centers, motor drives
- Enable adoption of EV/HEV, Solar PV, Wind, VFM, Aviation, Ship, Rail

| | |
|---|---|
| Power and voltage | ≥ 10 kW & ≥ 600 V |
| Efficiency ($Q = P_{out}/P_{loss}$) | ≥ 97.5% (Q ≥ 39) @ rated power<br>≥ 95% (Q ≥ 19) @ 5% rated power |
| Power density | ≥ 150 W/in3<br>(≥ 9.15 kW/L) |
| Specific power | ≥ 5 kW/kg |

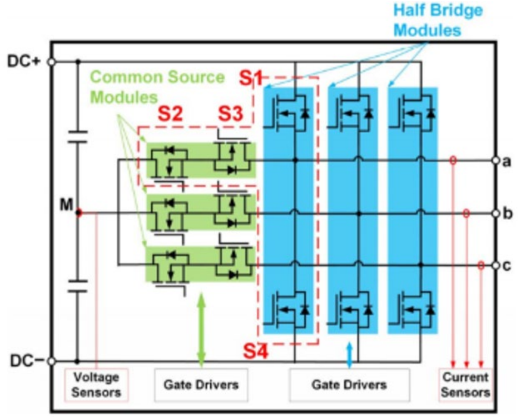
| | |
|---|---|
| EM Compliance | FCC Part 15 B |
| Cooling | Passive or forced air |
| Operation | 168-hour continuous basic operation |

CIRCUITS Performance Metrics

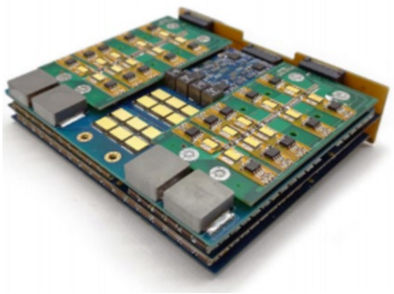
# CIRCUITS: Projects on Ampaire Electric Aviation Testbed

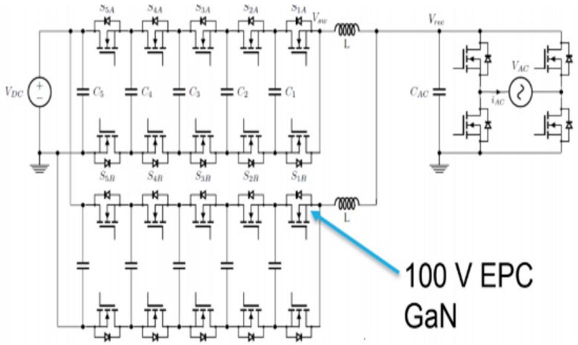



## University of Arkansas: 250 kW Motor Drive

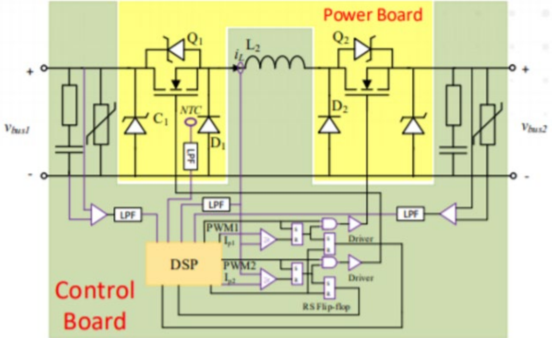



## UC-Berkeley: 10kW Flying Capacitor Converter






## IIT: 800V/240A iBreaker (DC Circuit Breaker)


**Other CIRCUITS, CABLES, ASCEND, REEACH, INTERGRATE next**

# BREAKERS

Program Director: Isik C. Kizilyalli

## Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely

2018, $23 Million
7 projects

**Enable and create MVDC markets in the range of 1.5kV – 100kV by developing novel DC circuit breaker technologies.**

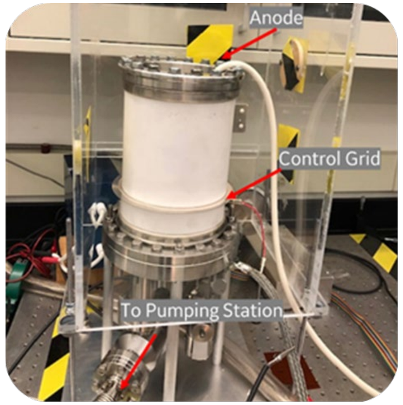
- MVDC has potential applications in grid resiliency, renewable and storage interconnection, electric aviation, electric ships, and oil & gas.
  - It can save 1.1 quads of energy per year, reduce U.S. emissions by 3% via electrification of transportation, and lower offshore oil and gas rig costs by 5%.
- High speed, low-loss MVDC circuit breakers will enable MVDC markets by providing circuit and electrical equipment protection (e.g. power converters, power lines).

| | |
|---|---|
| Rated voltage | 1 kV DC - 100 kV DC |
| Rated power (instantaneous) | ≥ 1 MW |
| Efficiency | ≥ 99.97% |
| Response time | ≤ 500 μs |

| | |
|---|---|
| Lifetime | ≥ 30,000 cycles, ≥ 30 years |
| Nuisance trips | ≤ 0.1% |
| Power density | ≥ 60 $MW/m^3$ |
| Cooling | Passive or forced air |

BREAKERS Program Technical Requirements

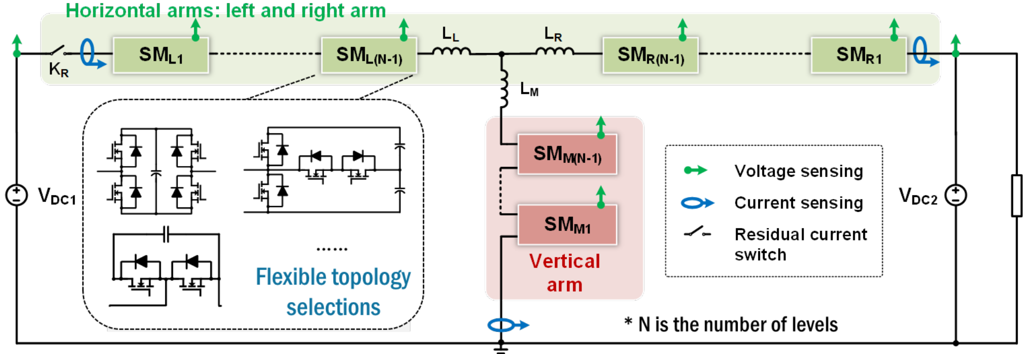
# BREAKERS enables MVDC markets in the 1.5kV – 100kV range




GE Global Research

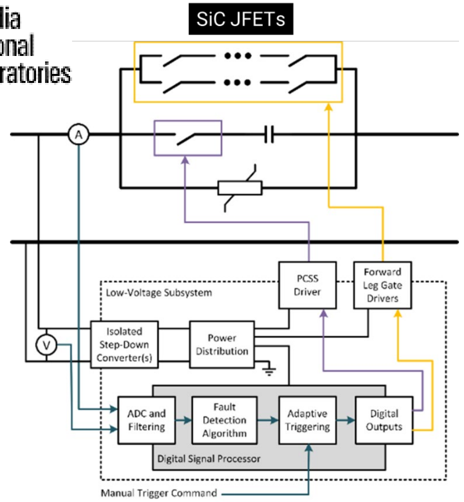
## Inline Gas Discharge Tube

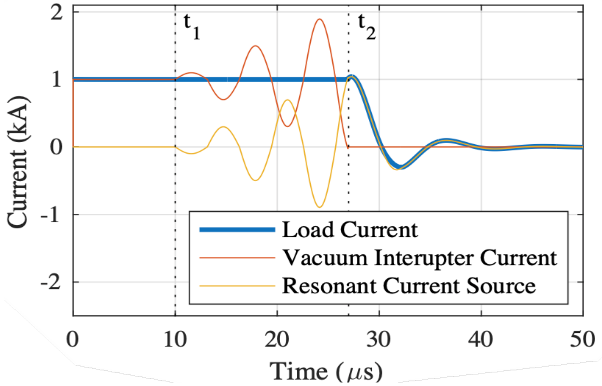
## Solid State Medium Voltage DC Circuit Breakers



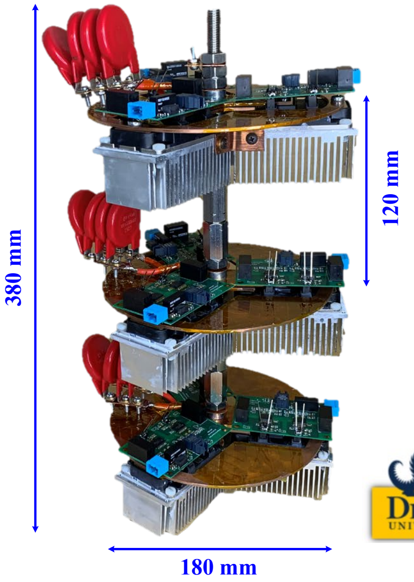

The Ohio State University

Sandia National Laboratories



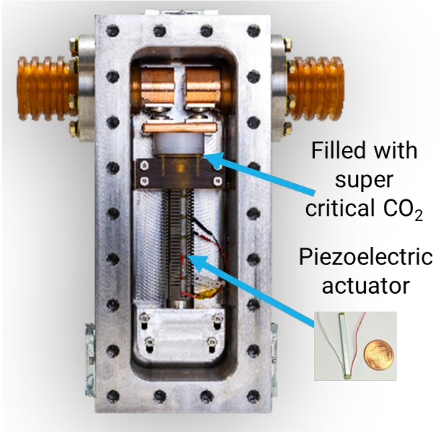

Marquette University

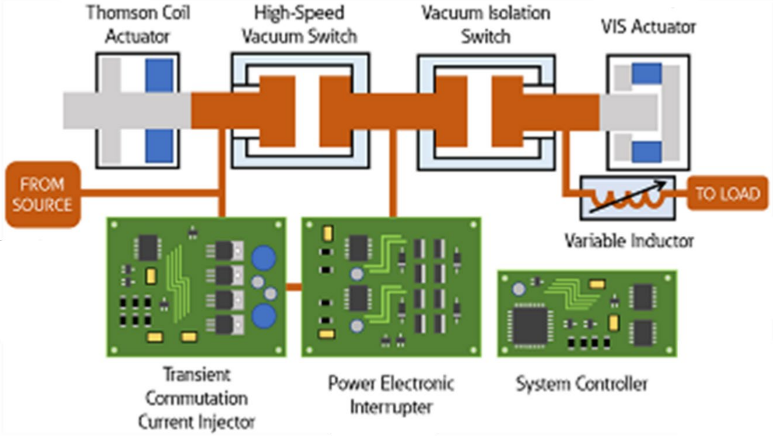



Drexel University

## Resonant Medium Voltage DC Circuit Breakers

## Hybrid Medium Voltage DC Circuit Breakers



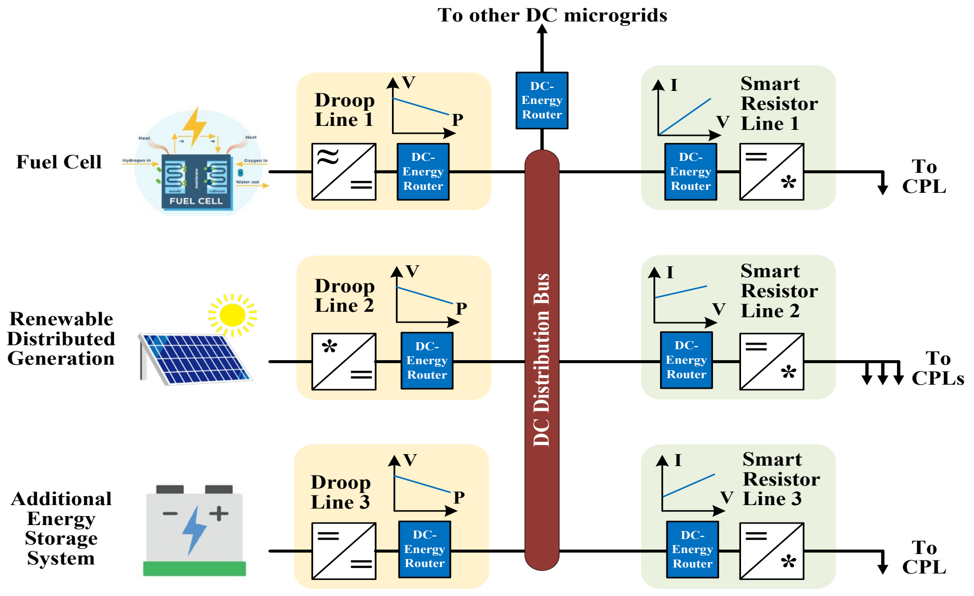



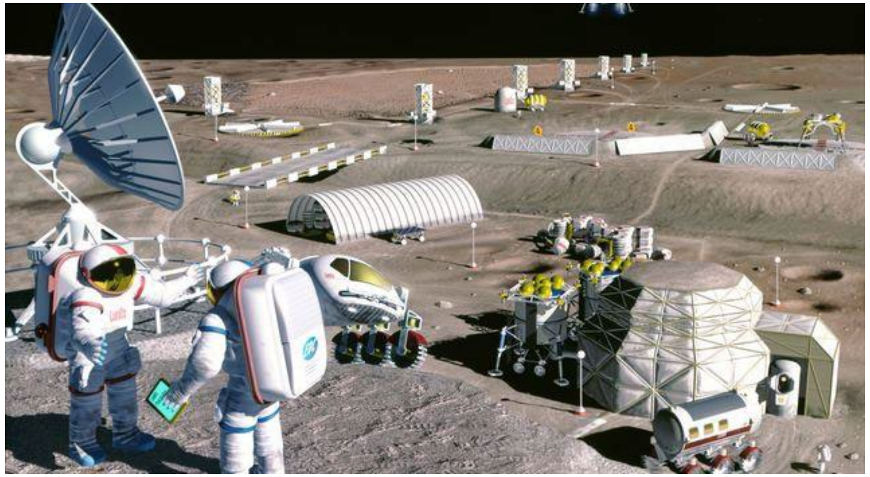

Georgia Institute of Technology

EATON Powering Business Worldwide

# Microgrids in Space

**Flexible DC Energy Router based on Energy Storage Integrated Circuit Breaker,** NASA Lunar Surface Technology Research, May 2021~May 2023, PI: Jin Wang



The project is to combine OSU's T-Breaker and Smart Resistor* concepts to create and demonstrate a modular DC-Energy Router for interconnected dc microgrids on lunar surface. A digital twin and a 120-V 10-kW GaN based high power density prototype would be built.

https://www.nasa.gov/directorates/spacetech/strg/lustr/2020/Flexible_DC_Energy_Router/
*K. A. Potty, E. Bauer, H. Li and J. Wang, "Smart Resistor: Stabilization of DC Microgrids Containing Constant Power Loads Using High-Bandwidth Power Converters and Energy Storage," in IEEE Transactions on Power Electronics, vol. 35, no. 1, pp. 957-967, Jan. 2020, doi: 10.1109/TPEL.2019.2910527.

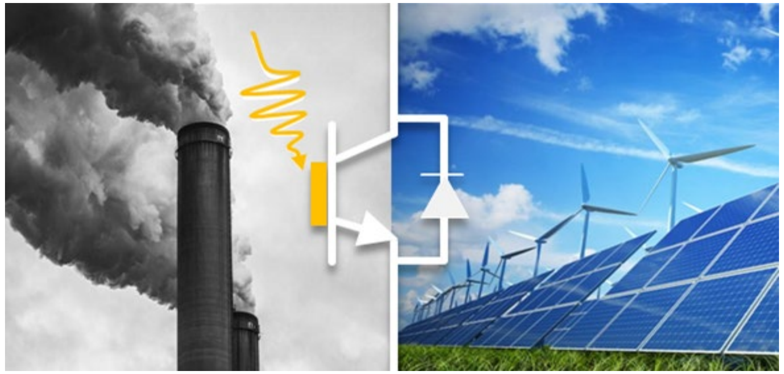
# ULTRAFAST

Program Director: Olga Spahn

## Unlocking Lasting Transformative Resiliency Advances by Faster Actuation of power Semiconductor Technologies


### Next generation material, device and module technologies for improved power distribution and control in future grid applications

- Enable future grid supporting Net-Zero Emissions goals by 2050
- Required for increased DER uptake, load electrification, and improved system resiliency



| Parameter \ FOA | Category 1 | Category 2 |
|---|---|---|
| Rated Voltage | ≥ 20 kV | ≥ 3.3 kV |
| Rated Current | ≥ 250 A | ≥ 10 A |
| Switching frequency | n/a | 1-100 kHz |
| Voltage slew-rate | ≥ 500 V/ns | ≥ 250 V/ns |
| Current slew-rate | ≥ 200 A/ns | ≥ 100 A/ns |
| Loss | ≥ 30% lower than SOTA | |

- UWBG materials for higher power individual devices and modules
- EMI mitigation for improved stacking, reliability
- Faster actuation – improved protection, better control, lower losses, better SWAP
- Supporting enabling technology – sensing, passives, packaging, gate drive technology

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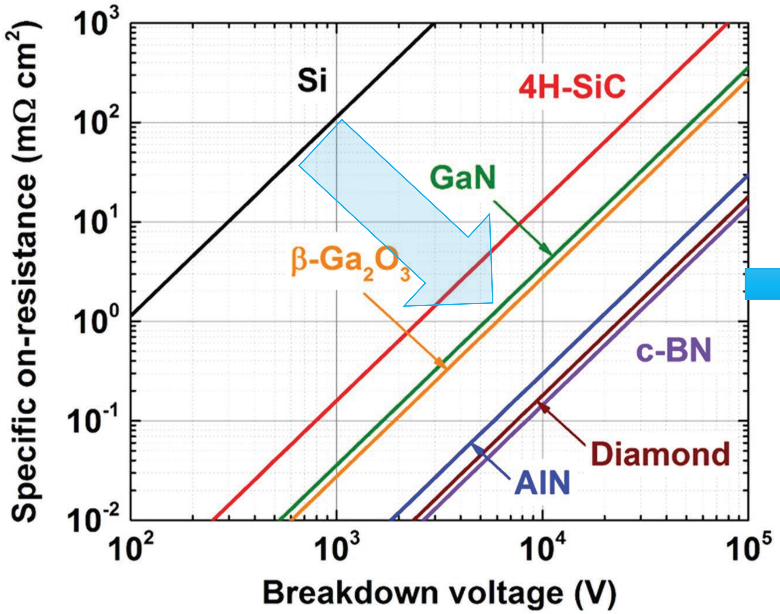
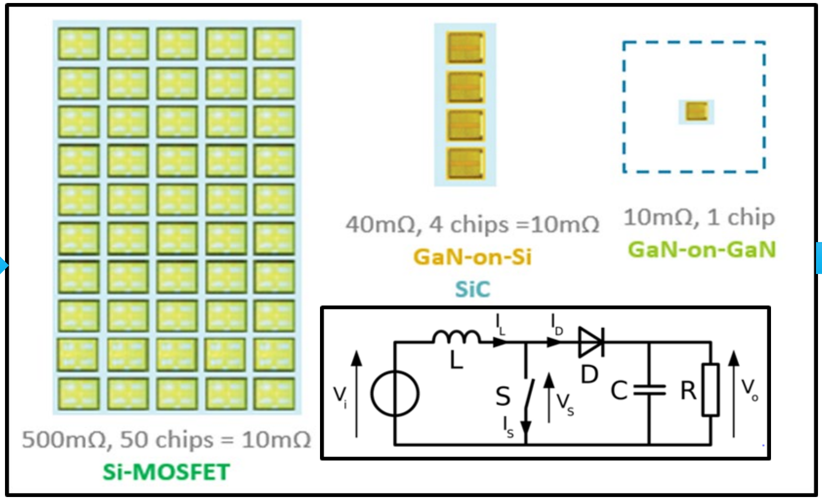
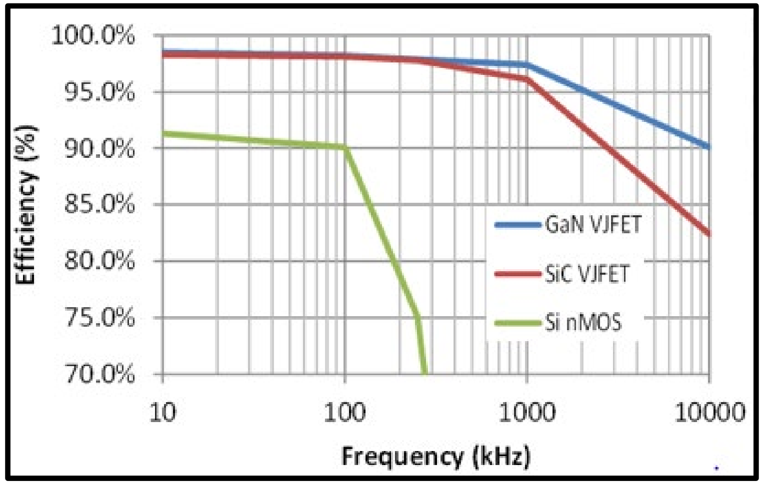
# UWBG Advantage in Power Electronics Devices and Systems

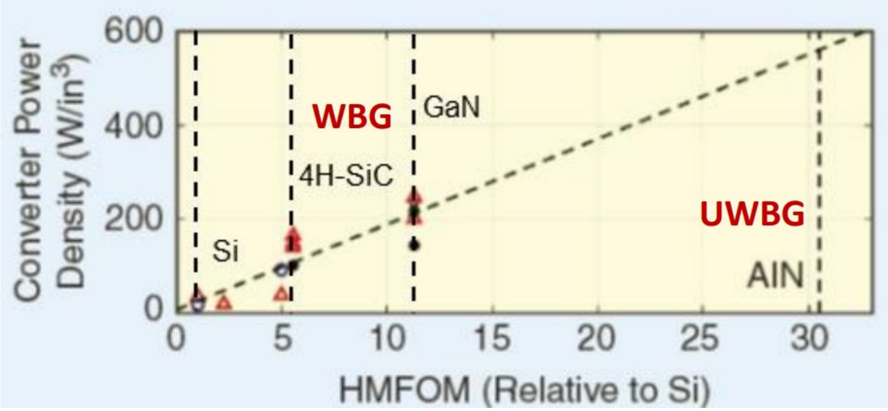



Smaller devices with better performance

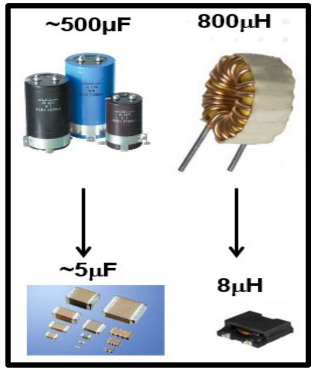



Faster switching with lower loss




UWBG>WBG>Si


Smaller power electronic systems




Need high frequency passives!

Smaller passives

**UWBG semiconductors enable even *smaller, lighter, higher temperature, more efficient, reliable, and lower* cost power electronic systems**

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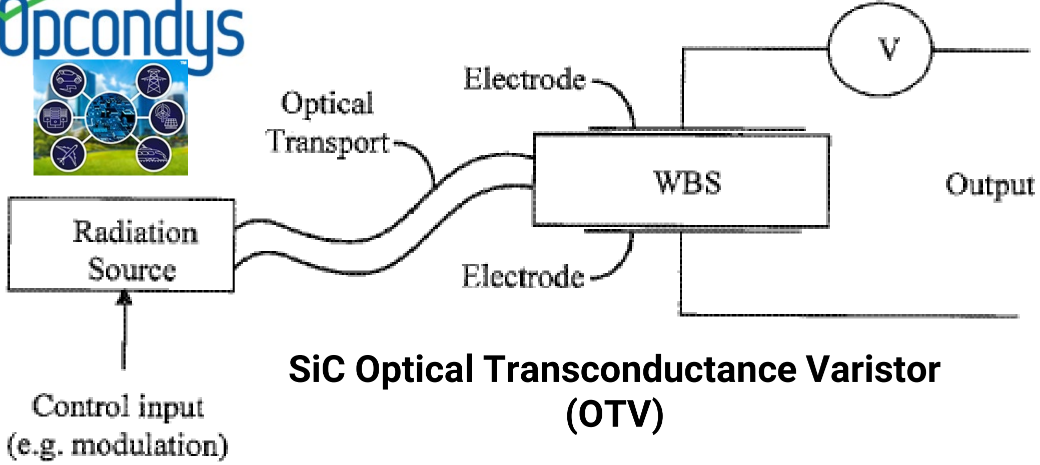
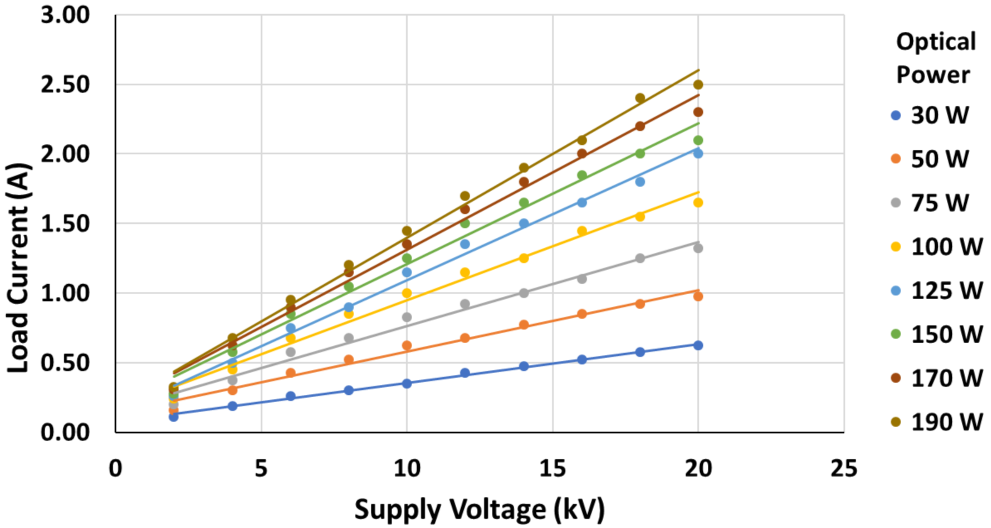
# Photoconductive Semiconductor Switch (PCSS)

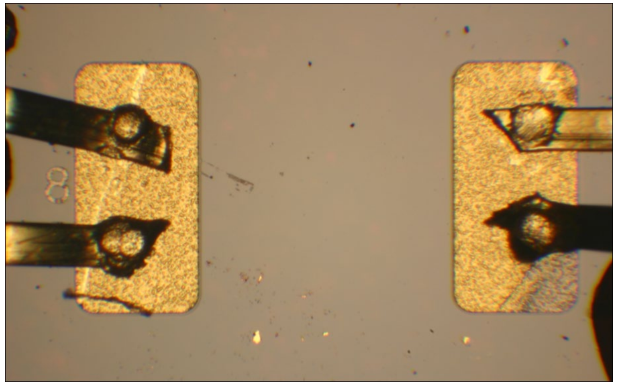



**SiC Optical Transconductance Varistor (OTV)**

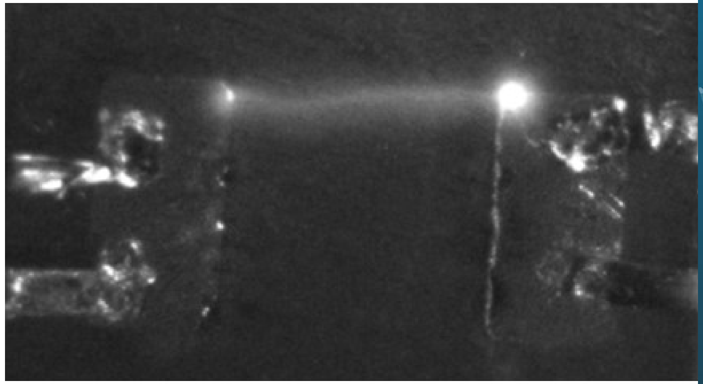



*US Patent Nos. 9,025,919, 9,142,339, 9,748,859, Int'l Pat. Pend.

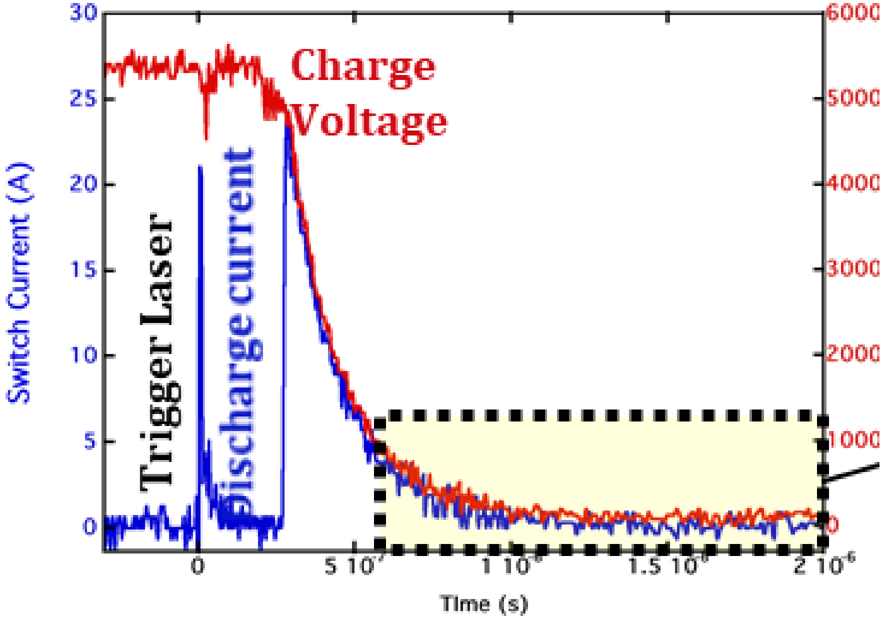
Optically induced conductivity



**GaN Lateral PCSS Device**



**Filamentary current conduction during high gain mode**




200 V "Lock-on" voltage

LTT – like, latching mode

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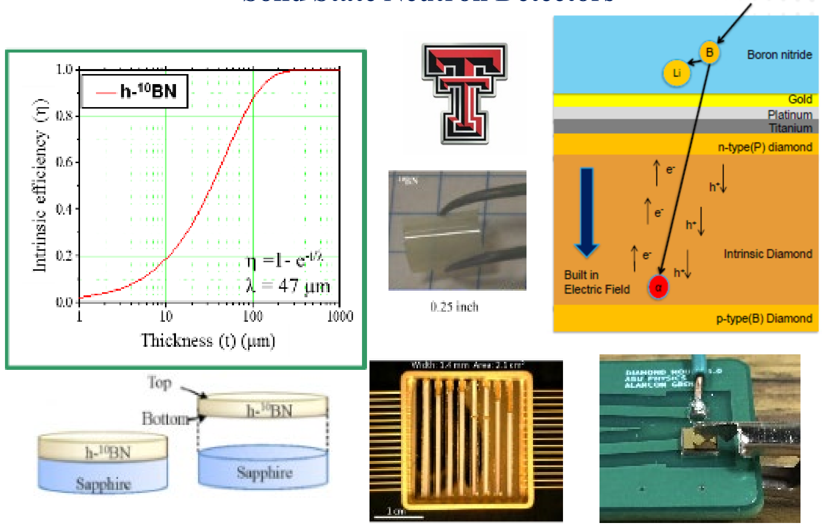
# Applications of Power Electronics

- In aviation (ASCEND, CABLES) – MV (>10kV) power distribution for electric aviation

- In subsurface technologies (OPEN2021)

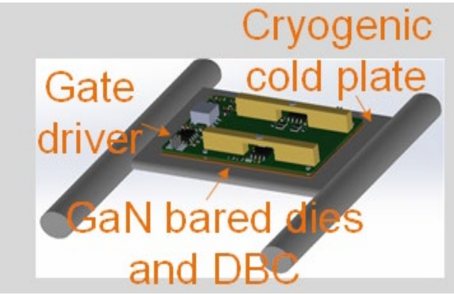
- In harsh environment sensing (OPEN2018,2021)

Solid State Neutron Detectors




OPEN2021

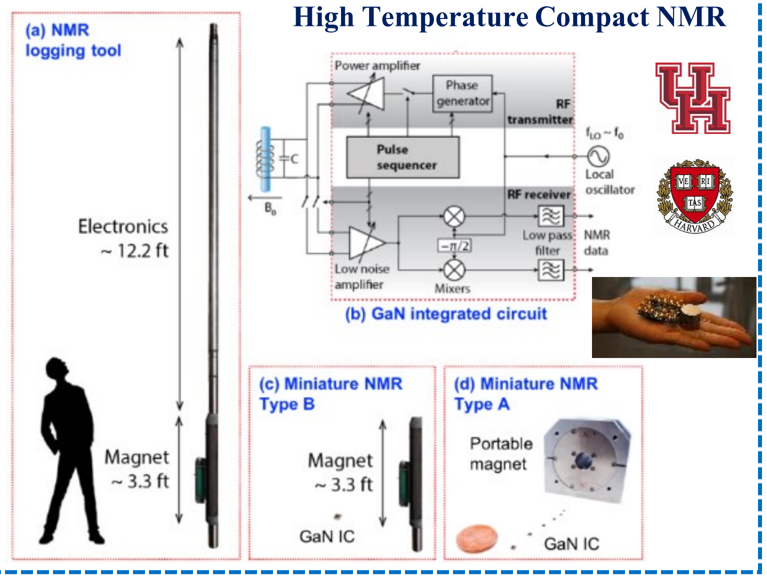
Cryo-cooled GaN-based SCCB for aviation platforms




THE UNIVERSITY OF TENNESSEE KNOXVILLE

CABLES

High Temperature Compact NMR




PLUTO (OPEN 2018, OPEN2021)

# What Could be Next for ARPA-e and Power Electronics

- OPEN 21($175M/68 Projects in Negotiation)
- SCALEUP 2023 for ARPA-e Alumni Projects
  - CIRCUITS
  - BREAKERS
  - SWITCHES and OPEN18
- ULTRAFAST
- OPEN 24
- Novel Power Electronics Circuits
- Magnetic Materials Development
- AlGaN, ScAlN, BAlN, BN based Devices
- Light Triggered WBG/UWBG Devices
- Bi-Directional and Super-Junction Switches and Circuits
- More Applications (Grid, MVDC, Aviation, Fusion, Nuclear Detect/Store, EGS)
- Baseline Process Flow in Foundry for GaN development


Source: BloombergNEF, ARPA-E

# Overarching Goals in Power Electronics

- **Transforming Energy Technologies: Efficiency with Deep De-carbonization**
- **Compact, Efficient, and Reliable Power Electronics**
- Electrification of Transportation and **Aviation** (includes Land Infrastructure)
- Variable Frequency Drives
- Integration of Renewables/Storage and **Grid Resiliency**
  - **Catalyze MVDC Distribution Market**
  - **Develop Enabling Technologies**
  - **MV, Novel Devices, and Power ICs**
- **Leverage Power Electronics** in Generation (EGS, Nuclear Fusion, Oil/Gas, Pulsed Power Drilling)

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