AMMTO Peer Review
Technology Area Overview

Power Electronics Manufacturing

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Overview

- **Why power electronics?**
  - Power electronics are needed for economy-wide electrification for decarbonization
  - SiC current US manufacturing strength and global competitiveness
  - AMMTO has historical leadership
- **AMMTO's Activities**
  - AMMTO has a strong history in supporting power electronics innovation
    - PowerAmerica
    - FOA Projects
    - traineeships
  - PowerAmerica selected to compete for Renewal (Fall 2023)
  - Decadal Plan Roadmaps power electronics for clean energy and competitiveness (Soft-launched at peer review)

Power Electronics in the EERE context

Power electronics is a key enabling technology across multiple EERE offices:

- Critical for increasing the *energy efficiency* of all electricity-using equipment,
- Crucial for controlling power use for large variability in energy demand, including
  - *sustainable transportation (e.g. EV fast charging)*
  - *industrial processes (e.g. industrial motors & electrification)*
  - *Grid resiliency (e.g. intermittent renewable integration, responding to more variable demand, & extreme weather events)*

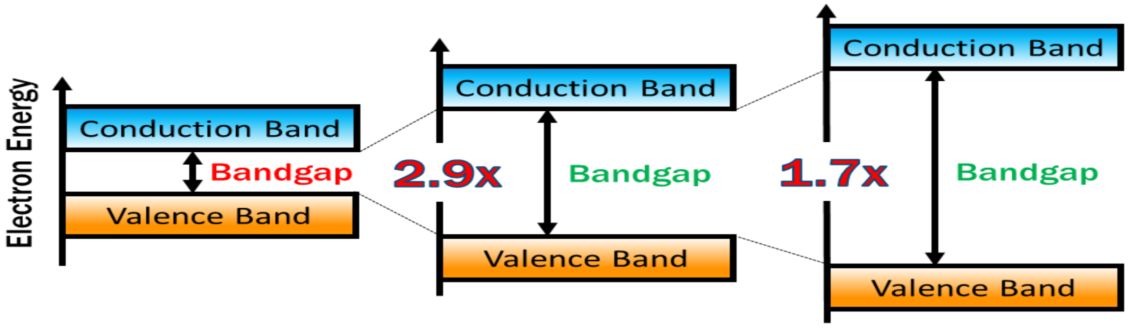
But costs need to drop in order to accelerate market adoption and achieve market transformation:
SiC PE devices are currently 3X the cost of Si devices.

Power Electronics Proposed Program Structure: Pyramid

Systems & Applications:
Full Systems including Passives

Assemblies:
Subsystems and Sub components

Materials and Devices:
Wafers, circuits & dice, modules



Conventional Semiconductors (e.g., silicon) — **High TRL**

Wide Bandgap (WBG) (e.g., silicon carbide) — **Mid TRL**

Ultra Wide Bandgap (UWBG) (e.g., diamond) — **Low TRL**

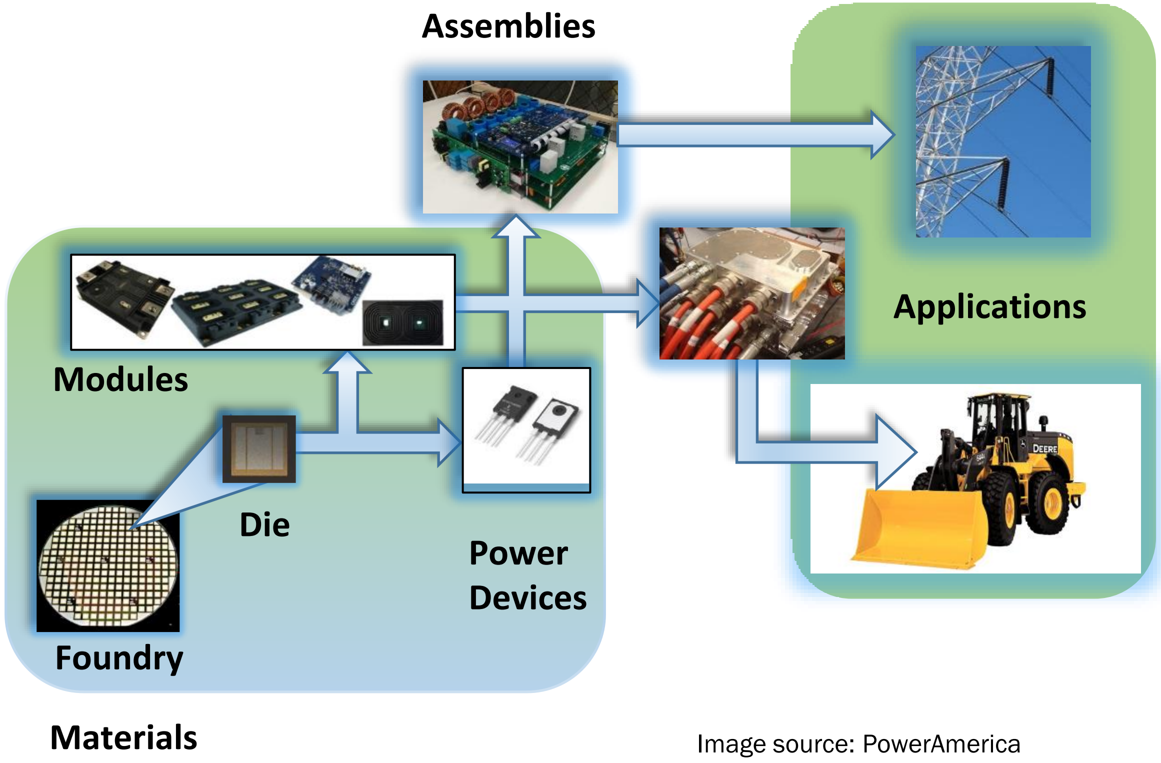


Image source: PowerAmerica

Benefits of increasing bandgaps:

- Smaller size & weight for same application
- Reduced energy losses
- Fewer & smaller passive components (e.g., capacitors, inductors, etc.) for high-power applications
- Increased energy efficiency

DOE Power Electronics Recent Key Investments

Office of Science

Foundational and exploratory research

ARPA-E

High-risk, transformative PE technologies

ADEPT (Agile Delivery of Electrical Power Technology) - 2010
SWITCHES (Strategies for Wide-Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems) - 2013

Advanced Materials & Manufacturing Technologies Office

- Maturing (e.g., reducing costs) PE manufacturing processes and technologies
- Catalyzing domestic PE manufacturing
- Collaborating with DOE offices, national labs, SBIR across clean energy applications

PowerAmerica – 2015
Next Gen Electric Machines – 2015 and 2016

Building Technologies Office

Energy efficient building technologies,

Vehicle Technologies Office

Electric vehicles and charging infrastructure

Advanced PE & Electric Motors (APEEM) R&D -2005

Solar Technologies Office

Utility-scale and distributed solar

Office of Electricity

Energy storage and grid systems

Energy Storage PE Program - 2016

Early stage → **** Manufacturing platform development**** → *Application-specific*

Power Electronics Historical Investments

	FY	Description	AMMTO Investment
Power America	2014-2020	Wide-Band Gap (mainly Silicon Carbide (SiC)) devices and systems	$70,000,000
SBIR	2022	Highly integrated, low cost SiC power modules with modified substrates for high performance and ease of manufacturing.	$200,000
Traineeships	2016-2022	UT Knoxville, VATech,	$3,500,000
FOA/LC	2019	Rapid, non-destructive detection of defects in Thick-GaN bulk	$3,960,000
	2019	Improving SiC Wafers and Processing for Lower Costs and Higher Reliability	$3,189,910
	2019	Grid Application Development, Testbed and Analysis for MV SiC	$7,500,000

PE Materials & Manufacturing Roadmap

Lead the development of a PE materials and manufacturing RD&D roadmap to address:

- Materials & Devices: Identify & support opportunities to mature UWBG manufacturing, maintain and strengthen WBG innovation, scale-up and cost reduction, include expand to conventional (silicon) power electronics where appropriate.
- Assemblies: Work with OE, ARPA-E, VTO on medium voltage for grid and transportation modernization and to enable decarbonization through electrification and a net-zero carbon grid by 2035.
- Systems and Applications: Include advanced Passives Develop WBG and Beyond PE for new large-scale industrial decarbonization applications

Two Parallel Tracks

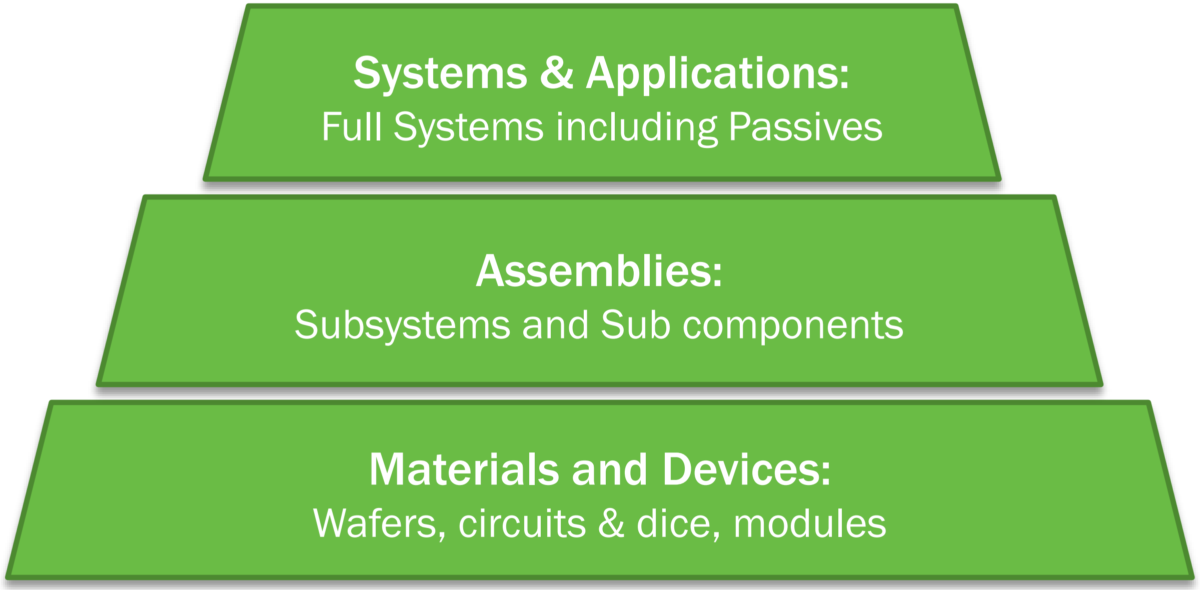
1. **DOE Offices:** Internal communication with offices to strategically connect all ongoing efforts & roadmaps
2. **National Labs (SNL, NREL, LLNL):** technical analysis and thought leadership on key material & manufacturing issues, gaps, indicators of progress, and future milestones.

Roadmap to identify PE RD&D and workforce targets, timelines, and convene key stakeholders

Panel Discussion: Developing a Power Electronics Roadmap

Panel Discussion Presentations:

- **Victor Veliadis** (NCSU): PowerAmerica
- **Robert Kaplan** (Sandia): Power Electronics Decadal Plan support
- **Chris Irwin** (DOE Office of Electricity): Power Electronics to Support Grid Modernization
- **Xiaoli Tan** (Iowa State University): Novel Ceramic Capacitors with ultrahigh energy density and efficiency for passive power electronics components



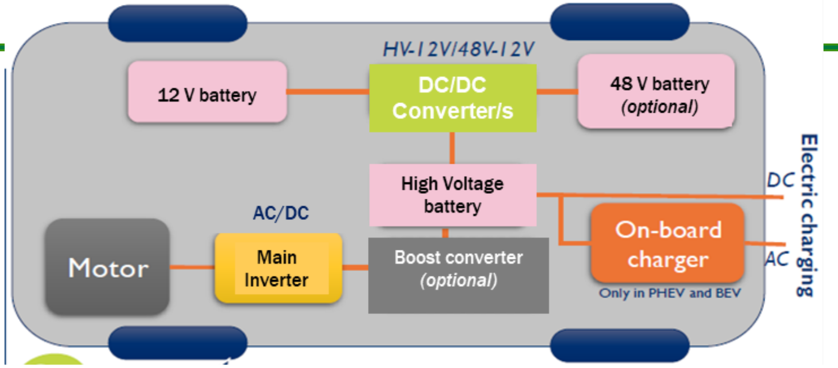
Backup/ Reference

Key Applications

Electric Vehicles:

- Improving inverter efficiency (main inverter, boost inverter, DC-DC converter, on-board charger)
- Impacts:
    - Improved vehicle efficiency (↓**weight**, ↑**MPGe**)
    - Faster charging times

1,120 TBtu of potential energy savings in EVs by 2050 if SiC replaces silicon

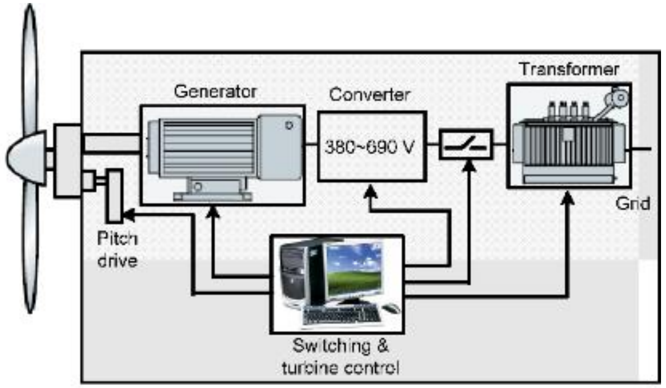


Source: Yole Power SiC 2022

Renewables:

Wind

- Improving wind turbine converter efficiency
- WBG can result in improved products and accelerated market uptake
- **Impacts**: 101 TBtu of potential energy savings by 2050 if SiC replaces Si

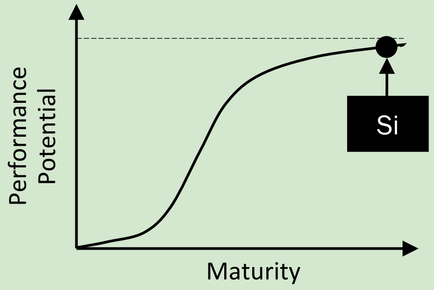
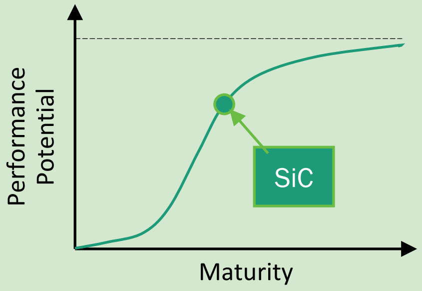
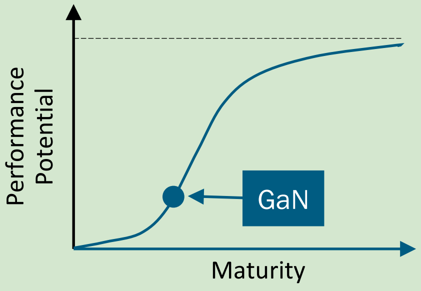


Solar PV:

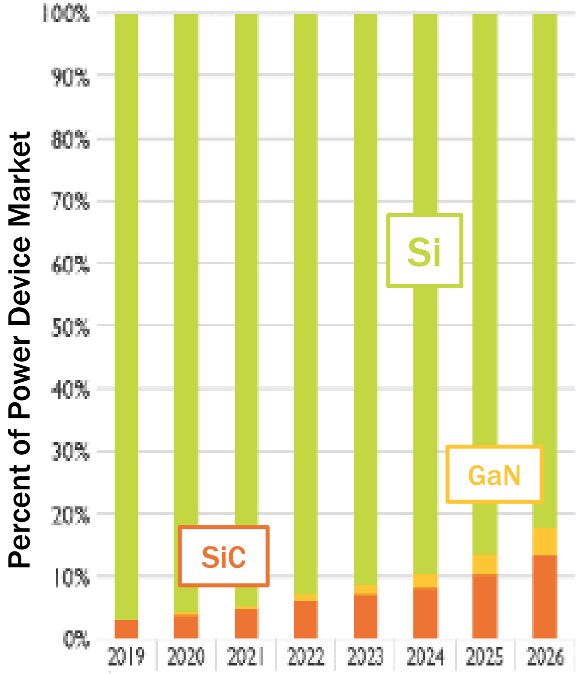
- Improving PV inverter efficiency
- **Impacts:** 99 TBtu of potential energy savings by 2050 if SiC replaces Si

Wide bandgap (WBG) PE offers significant advantages

WBG still needs materials & manufacturing improvements

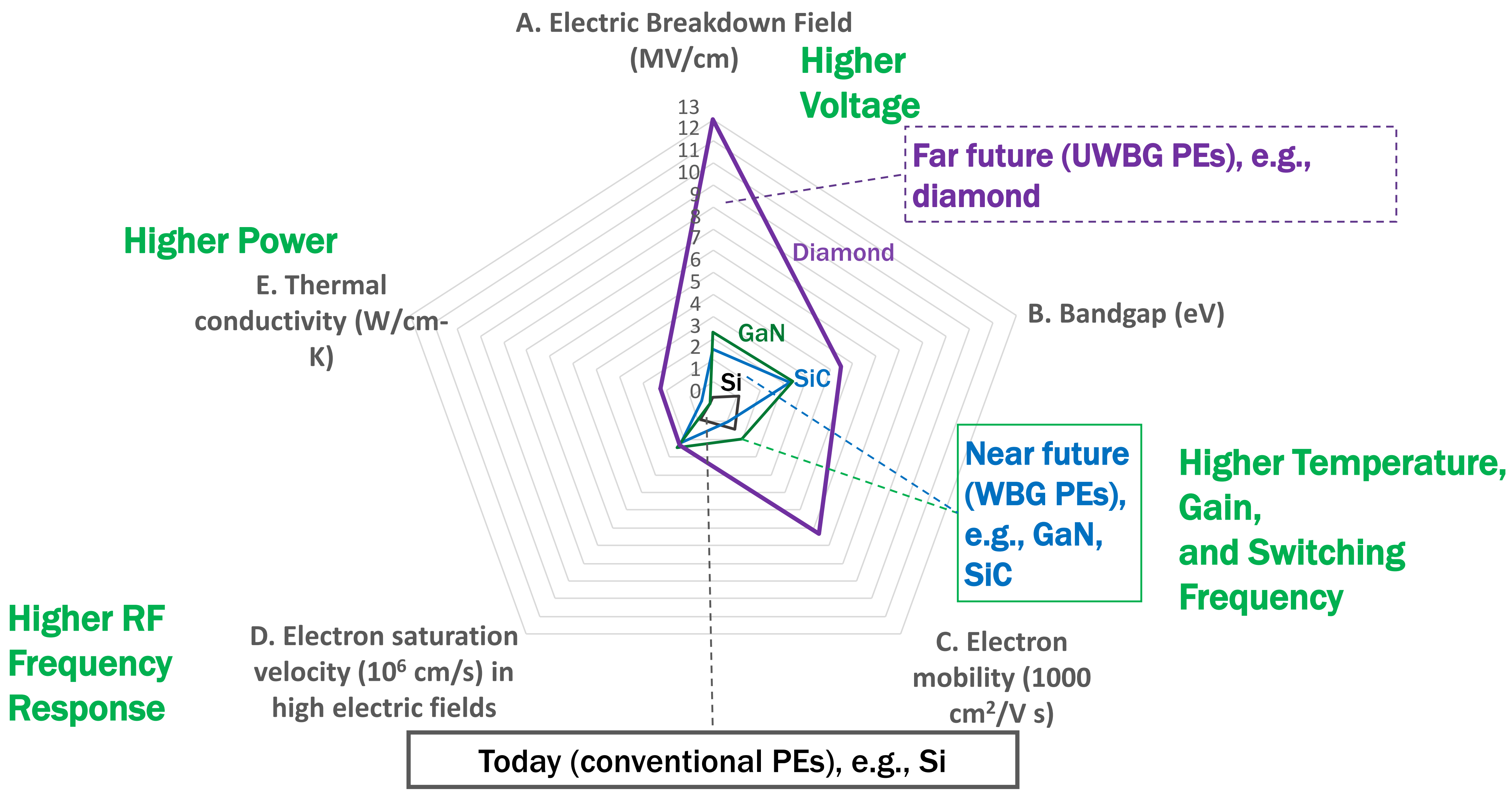
	Silicon	Silicon Carbide	Gallium Nitride
Maturity			
Advantages	• Highly mature technology • High reliability • Availability of design tools • Cost per performance	• High temperature (>300ºC) • High voltage (kV levels) • Good thermal conductivity	• Better figures-of-merit • High system density • Potential for CMOS integration
Barriers to Adoption	• Performance limits for some applications • ***Switching losses / inefficiency***	• Low mobility • High device-level cost	• Limited native substrates • Poor p-GaN conductivity • Maturity ~1 decade behind SiC

Silicon market share in light green



Yole, PowerSiC 2022

Materials Performance: WBG and Beyond



AMMTO will focus on lowering WBG cost

SiC is now 3X > cost of Si Power Electronics

AMMTO plans to decrease SiC materials and component costs by

a) Reducing cost and energy used to grow SiC boules (now requires >2,000°C)
b) Eliminating defects from basal plane dislocations and other sources to improve wafer and device quality
c) Improving SiC slicing process which now requires 10-20X longer to slice than Si
d) Increasing robustness for manufacturing thinner SiC wafers (now prone to cracking and chipping)

GaN on GaN is now 6-12X > cost of Si Power Electronics

AMMTO plans to decrease GaN materials and component costs by

a) Improving understanding of material chemistries/solubilities and impact on growth rate and crystal quality
b) Eliminating point defect impurities
c) Improving GaN thinning and slicing processes especially to enable more robust packaging
d) Improving thermal and lattice matching to avoid stresses and wafer bow
e) Lower epitaxial growth temperatures to avoid GaN crystal structural impacts
f) Decreasing cost of GaN epitaxy on substrate process
g) Increasing yields by increasing substrate diameter

AMMTO plans to decrease power electronics' materials and component costs in general by

a) Increasing skilled workforce for more domestic manufacturing and lower costs.
b) Rapid scaleup of new processes for materials and components

U.S. DEPARTMENT OF ENERGY

Developing Power Electronics Manufacturing Capabilities

AMMTO-sponsored institute PowerAmerica facilitates access to equipment and facilities needed to research, development, and scale-up. This lowers the barrier of technology development for companies without these facilities, particularly small and medium businesse

Challenge: Research and Development and manufacturing equipment is costly. However, access to this equipment is necessary for technology development and scale-up.

Achievement:
PowerAmerica partnered with X-Fab to create the worlds first open silicon carbide foundry, removing a significant barrier to commercialization of wide band gap power electronics technologies.

PowerAmerica's X-Fab Silicon Carbide Foundry is the first open silicon carbide foundry. Photo courtesy of X-Fab Silicon Foundries

Each year 15-20 American companies use X-Fab to progress technologies towards commercialization.

Institutes facilitate the establishment, vetting, and use of shared facilities that can significantly lower the barrier and cost to develop technologies for commercialization.

Power Conditioning Systems(PCS): Highlights

FOA-0001980 – AMO-FY19MT

TA3.1: Medium-Voltage Power Conditioning Systems to Enable Grid-Dispatchable and Resilient Manufacturing Facilities

- DE-EE0009133 – Virginia Polytechnical Institute
  - Partners: Siemens
  - Budget: $4M FED, $1M CS, TPC $5M
- DE-EE0009134 – University of Tenn.
  - Partners: GEGR, ORNL
  - Budget: $3.6M FED (75K ORNL), $0.9M CS, TPC $4.5M
- DE-EE0009135 – Eaton Corporation
  - Partners: Broadcom, NCSU
  - Budget: $4M FED, $1M CS, TPC $5M

FOA Goals and Objectives:

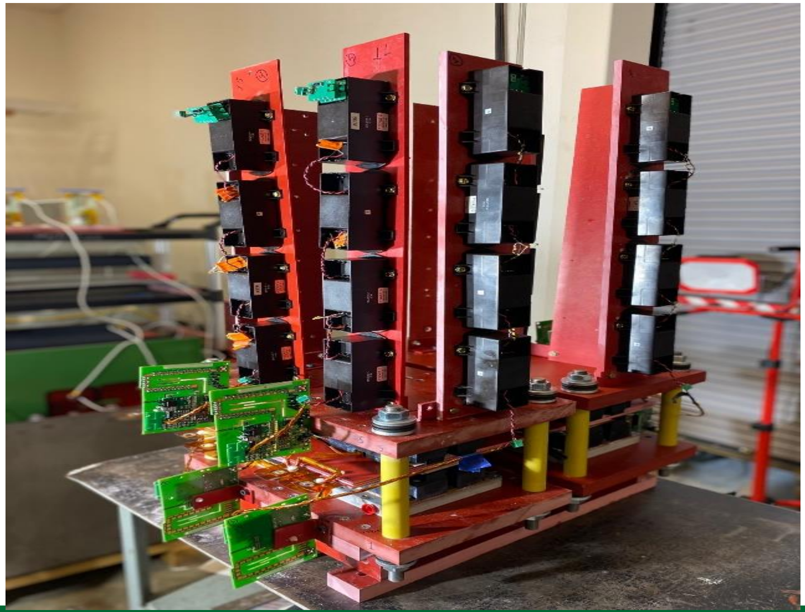
Subtopic 3.1 Objective/Goal	Metric	Minimum	Stretch Target
Increase manufacturing plant dispatchable load/generation without process interruptions	Calculated increase in dispatchability for PCS use cases compared to existing plants	>10% over applicant defined baseline	20%
Increase efficiency of 13.8 kV inverters	Full load efficiency per 13.8 kV inverter	>99.4 %	>99.7
Decrease Manufacturing Cost of 10 kV SiC module-based power electronic assemblies	Cost per 13.8 kV inverter excluding cost of SiC die	<$30/kW	<$15/kW
Increase service life of 10 kV SiC module power electronic assemblies	Calculated using existing qualification standards and partial discharge tests	> 10 years	> 30 years
Compact 13.8 kV power electronic assemblies	Each 13.8 kV three phase inverter volume	0.3 m3 per MVA	0.15 m3 per MVA

Progress overview

- **DE-EE0009133/VT**
  - Project is in middle of BP2, BP2 ends 9/30/2023 – likely delayed.
  - 10kV Wolfspeed Module performance issues persist, may impact ability to accomplish remaining project scope.
- **DE-EE0009134/UTK**
  - Project is in later part of BP2, BP2 ends 6/30/2023 – NCTE expected.
  - 10kV Wolfspeed Module performance issues persist, may impact ability to accomplish remaining project scope.
- **DE-EE0009135/Eaton**
  - Expect to complete BP2 GNG by 4/30, preparing to submit CA, ends 7/31/2023 – on schedule.
  - Designed unique modules and fabricated by POWEREX
  - Requested revision to FWW for partner PWP in March 2023
  - No immediate scope, schedule, or budget concerns.

A joint meeting with all recipients was held at Eaton facility in late 2022 to discuss 10kV module issues and lessons learned w.r.t. previous Eaton NGEM project DE-EE0007253. Discussions are on-going between all teams about how to solve the 10kV module issues.

Source: UTK



Source: Eaton

Lab-based PE Project Summary Slide

LAB	WBS No	Title	PI	Project End Date	Status
NREL	1.2.5.10	Improving SiC Wafers and Processing for Lower Costs and Higher reliability	Mowafak Al-Jassim	March 31, 2023	Pending final report.
NREL	1.2.1.2	Grid Application Development, Testbed, and Analysis for MV SiC (GADTAMS)	Barry Mather	June 30, 2023	All but one milestone completed.
LLNL	1.2.5.9	Rapid Non-Destructive Detection of Defects in Thick GaN Bulk	Ted Laurence	March 31, 2023	Pending final report.

Lab-based PE Project Highlights - GADTAMS

Goal:
Develop a viable pathway for integration of medium voltage (MV, e,g, 13.8 kV) SiC power electronic into the utility system (grid) to achieve maximum system benefits such as: reduced losses, increased operating flexibility, improved reliability and resiliency, and greater functionality at a low cost.

Budget:
$7,500,000 federal share

Objectives:
1) Develop the capability to test MV direct-connected SiC-enabled power electronics in an open-access lab with the intent of using such capability to prove out necessary grid-based functionality,

2) Analyze the benefit of directly-connected MV capable power electronics that don't require a step-down line-frequency transformer via power system simulations.

3) Development and prototyping of a back-to-back MV directly-connected converter that would interconnect microgrids to other microgrids, and microgrids to the larger distribution system (i.e., macrogrid).

Status:
Period of Performance ends June 30, 2023.