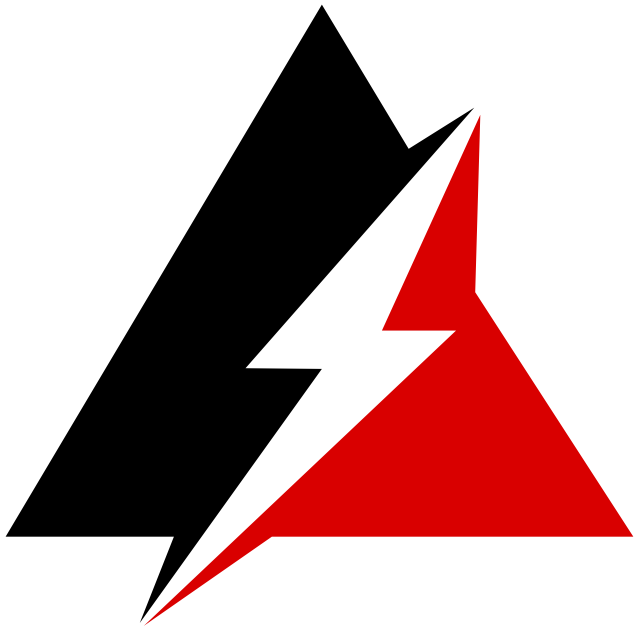


PowerAmerica

Draft Public Roadmap

May 2016

Strategy for Wide Adoption of WBG Semiconductor Devices

Vision

Accelerate Wide Adoption of WBG Semiconductor Devices in PE Systems

Strategy

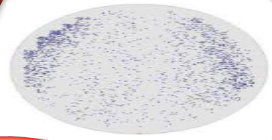
- Highlight Performance Advantages of WBG Devices
  Stress high voltage at low resistance, high temperature, and high frequency WBG device operational advantages over those of *Si* counterparts
- Establish Reliability of WBG Devices
  Leverage *Si* Reliability best practices in developing WBG reliability standards
- Showcase System Insertion Advantages of WBG Devices
  - Develop packaging technology that allows for full WBG performance potential
  - Demonstrate WBG PE system value proposition in terms of higher efficiency, and smaller weight/volume at low overall additional system cost
- Reduce Cost of WBG Devices
  Leverage mature *Si* fabrication practices, and qualify WBG specific processes to enable multiple source high-yield volume production
- Train Workforce in WBG devices/modules/systems

Benefits

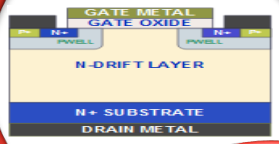
Job Creation, Accelerated Technology Innovation, Energy Savings, Smaller Environmental footprint

WBG Ecosystem Spans Numerous Industries

Wafer Suppliers

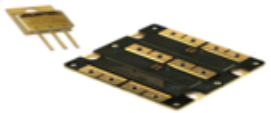


Device Design Houses



Wafer Fabs

Reliability and Packaging Fabs



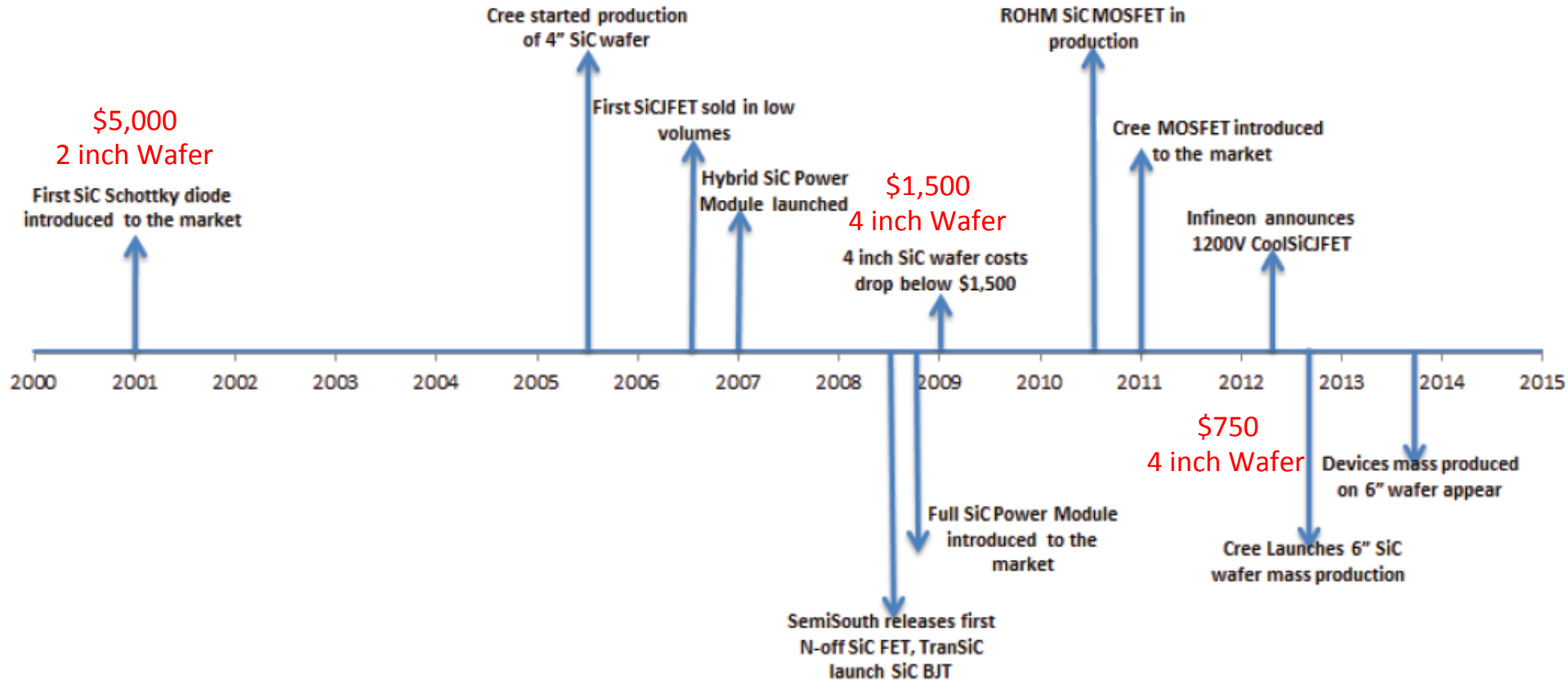
Market Demand Feedback

WBG Roadmapping requires a clear understanding of industry interplay

OEMs

Wafer Cost Reduced with Volume

Credit: IHS Technology (http://technology.ihs.com): *The World Market for Silicon Carbide & Gallium Nitride Power Semiconductors* - 2013 Edition



Manufacturing volume lowers wafer costs. Larger area wafer lowers device cost.

**Modified from DOE Quadrennial Technology Review Ch 6N*

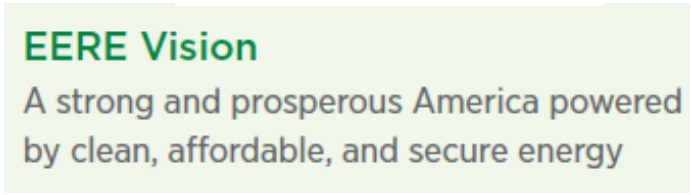
Government and Industry Documents Contribute to Roadmap

- **Strategic Government Policy Documents**
  - Quadrennial Energy Review (QER)
  - Quadrennial Technology Review (QTR)-CH 6N.
  - Advanced Manufacturing Partnership 2.0
    - (NEC / PCAST 2014/ OSTP 2014)
  - Quadrennial Defense Review (QDR)
    - Naval S&T Strategic Plan
    - Army S&T Campaign Plans 2015-2035
    - DOD Energy and Power Roadmap (2015)


NATIONAL NETWORK FOR MANUFACTURING INNOVATION PROGRAM
STRATEGIC PLAN

Executive Office of the President
National Science and Technology Council
Advanced Manufacturing National Program Office

February 2016


EERE Vision

A strong and prosperous America powered by clean, affordable, and secure energy

- **WBG Power Semiconductor Roadmaps**
  - USDRIVE, Electrical and Electronics Technical Team Roadmap, June 2013
  - ARPA-e, *A Pathway to Commercialization of Wide Bandgap Semiconductors in Power Electronics*, March 2015
  - PEIC, *Driving Collaboration for Power Electronics Technology Roadmapping Review*, Nov. 2015
  - PSMA, Power Technology Roadmap Trends 2014-2019, 2015
  - ETH – *ECPE Roadmap, Vision – Power Electronics 2025*, 2015

Market Research Findings Contribute to Roadmap

- **Market Driven Roadmaps**
  - *GaN and SiC Devices for Power Electronics Applications*, August 2015
  - *GaN and SiC and WBG Materials for Power Electronics Applications*, October 2015
  - *GaN Devices for Power Electronics – Patent Investigation*, 2015
  - *Wide Band Gap Power Electronics: A Path Toward CO2 Emission Decrease*, Yole presentation at Semicon West Conference, July 2014
  - *Market and Technology Trends in WBG Materials for Power Electronics Applications*, Yole presentation at the CS MANTECH Conference, May 2015
  - PEIC, NEXTEnergy, *Strengthening the Domestic Power Electronics Ecosystem*, Report on the Domestic Supply Chain Gaps in the Power Electronics Industry, April 2015
  - Point-the-Gap, *GaN & SiC Technology & Market Knowledge Update*, 2015
  - Ampere Laboratory, INSA de Lyon, *Wide Bandgap Power Devices GaN and SiC*, March 2015

PowerAmerica Roadmap Drives Investment and Project Selection

Driving Cost

1. Complete X-Fab investment to provide ability to run process without outsourcing steps.
2. Facilitate Introduction of companies to Foundry Model.
3. **Develop PowerAmerica Fabrication Process.**
4. Continue support of vertical integration with packaging.

Driving Reliability

1. Establish connections with PELs working group for SiC devices.
2. Establish connections with Texas Instruments, Infineon about JEDEC.
3. **Develop Independent Reliability Center.**

Accelerating Commercialization

1. Showcase System Insertion Advantages of WBG Devices.
2. Train workforce.
3. **Establish device bank to reduce lead time and improve accessibility.**

SiC Strategic planning

Diodes for Volume
MOSFETs for Potential transfer of existing Processes

PA enabled 1st products
X-fab In House Process complete

PA Process Used by Academia, Industry?

FA2: Device Fabrication
US Maintains Competitive WBG Fabrication of Devices and Modules

Initial SiC Foundry Capital Equipment Investment

Develop JFET, SJT HV Diode, MOSFET Processes

Packaging of improved through teaming and R&D. More focus on 3.3-10 kV

Big Road Mapping Questions:
How low in voltage will SiC Go? (Impact on Automotive, GaN)
Enough U.S. HV Packaging Expertise?
How can reliability best be communicated?

1st Devices Delivered to Device Bank

Reliability WBG Established

PV (due to Volume)

Increased Automotive

Data Center, UPS, Solid State Fuse

HV Grid

Increased HF magnetics, Passives

FA4: Accelerate Commercialization
PA enabled devices in John Deere Toshiba, ABB, and other U.S. Products

Wafer costs assumed to reduce over time due to increased volume

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024

GaN Strategic Planning

Triquint/RFMD Merger.
Tranphorm Fab. Japan
Navitas @TSMC

GaN Foundry in US could
Be important Second source,
Allow GaN Innovation.

FA2: Device Fabrication GaN
US Maintains Competitiveness In Design, I.P. and GaN Innovation

GaN Projects to US manufacturing Applications

Will Vertical GaN be Ready?
When 8 inch GaN/Si?

Improved Packaging, Improved P.E. Manufacturing Methods (Fred Lee)

Big Road Mapping Questions:
Timing of GaN Market Growth?
What Voltage will power GaN Excel?
Importance of Gate Drive Integration?
How to Leverage RF foundries?

1st Devices Delivered to Device Bank

Reliability WBG Established

PV (due to Volume)

Increased Automotive?

Data Centers, Consumer Elect. Adapters, Wireless Power

Increased HF magnetics, Passives

FA4: Accelerate Commercialization
PA enabled GaN Applications Manufactured in US.

Wafer costs assumed to reduce over time due to increased volume

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024

PowerAmerica Silicon Carbide Roadmap Drives Long Term Strategy

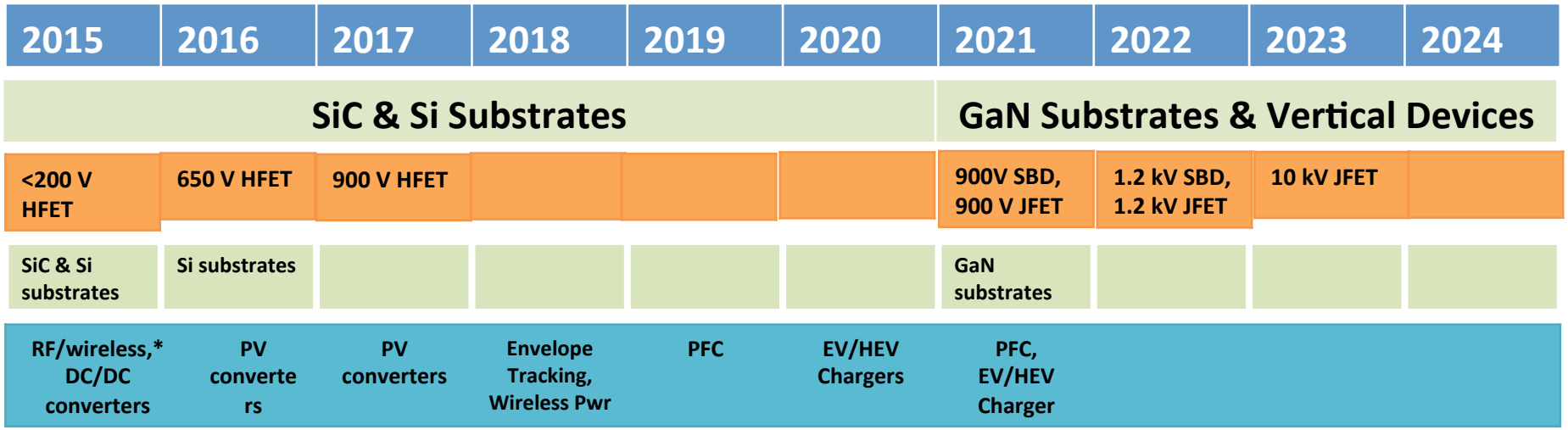
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
I	AEC-Q101 qual high-I_{DS} chips	175°C is T_{Jmax} for qual	650V – 175A chip @ 90C	1.2kV – 150A chip @ 90C	1.7kV – 125A chip @ 90C	2.4kV – 100A chip @ 90C	3.3kV – 50A chip @ 90C	4.5kV – 40A chip @ 90C	6.5kV – 30A chip @ 90C	6.5kV – 60A IGBT chip @ 90C
V	1.2, 1.7 kV SBD/FET	3.3 kV SBD/ FET	2.4kV SBD/ FET	4.5, 6.5 kV SBD/FET	6.5, 10 kV SBD/FET	6.5kV SBD/ IGBT	10 kV PiN Diode/IGBT	15 kV PiN Diode/IGBT	20 kV PiN Diode/IGBT	30 kV PiN Diode/IGBT
$	1.2 kV FET 40 c/A	1.2 kV FET 30 c/A	1.2 kV FET 25 c/A	1.2 kV FET 20 c/A	1.2 kV FET 15 c/A	1.2 kV FET	1.2 kV FET	1.2 kV FET	1.2 kV FET	1.2 kV FET
App	PFC, PV 5-10 kW	Power Supply	UPS/HVAC/ SSCB	PV 50-250kW, 1.5kV bus	EV Traction	MV VSD Automotive Chargers	Central PV 1-10 MW	DC dis. Data Servers	Wind	Grid power Flow
Frequency / Technology	40-100kHz LF DMOS	50-500kHz HF DMOS	40-100kHz HF trench	5-10kHz LF trench	10-30kHz LF/HF trench	5-10kHz LF IGBT	5-10kHz LF IGBT	0.1-1.0MHz HF IGBT	5-10kHz LF IGBT	5-10kHz LF IGBT

Enablers:

Packaging for low thermal impedance, +200°C, and low stray inductance
Soft Magnetics
Gate driver design

Device design services
Open access foundry services
Workforce training
Device bank to be introduced Fall 2016

PowerAmerica Gallium Nitride Roadmap Drives Long Term Strategy



Challenges:

Not clear when GaN Market will mature.

GaN community needs to unite for 2nd source foundry capacity.

SiC moving into GaN voltage space.

Opportunities:

GaN is increasing in voltage and reliability.

GaN Gate Driver Integration

GaN at lower voltages beats silicon in size and performance.