FREEDM SYSTEMS CENTER

POWERAMERICA

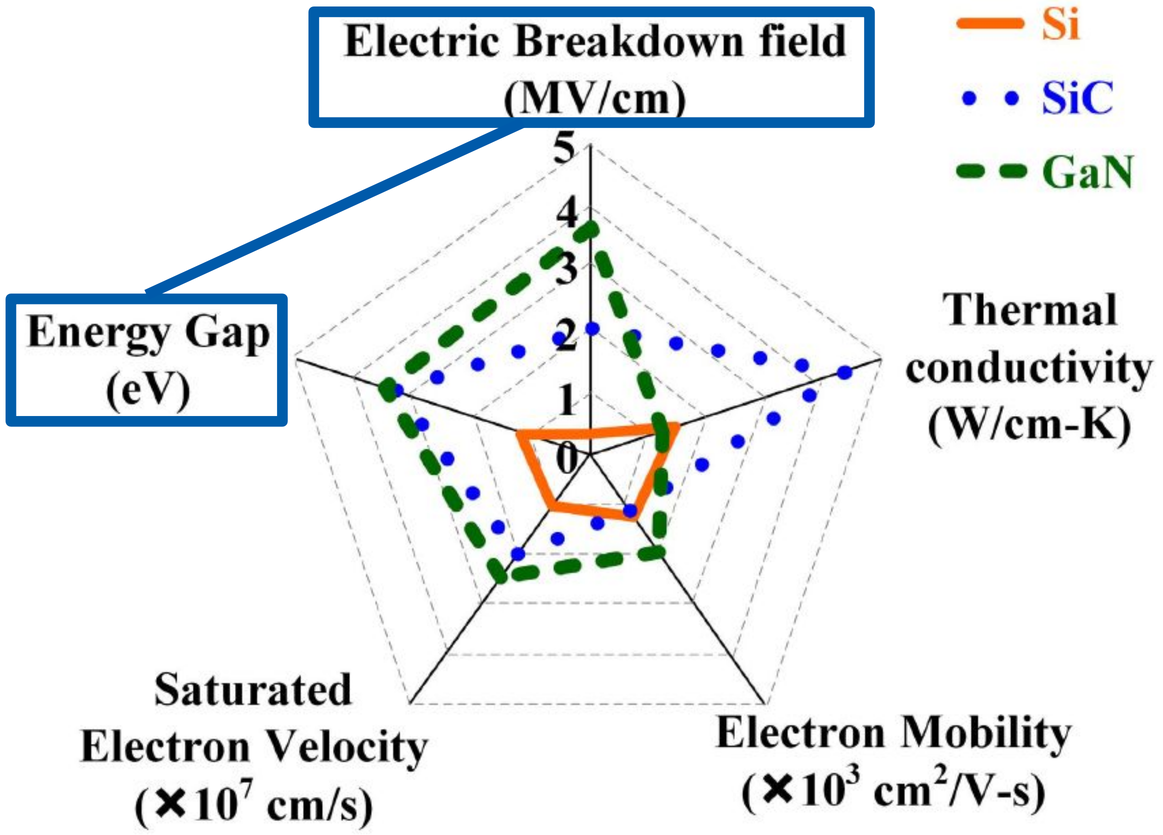
Accelerating WBG Power Electronics Commercialization

FREEDM Annual Meeting

April 11, 2019

Dr. Victor Veliadis
Deputy Executive Director and CTO, PowerAmerica
Professor ECE North Carolina State University, Raleigh, NC USA
jvveliad@ncsu.edu

GaN/SiC Power Devices Allow for More Efficient and Novel Power Electronics

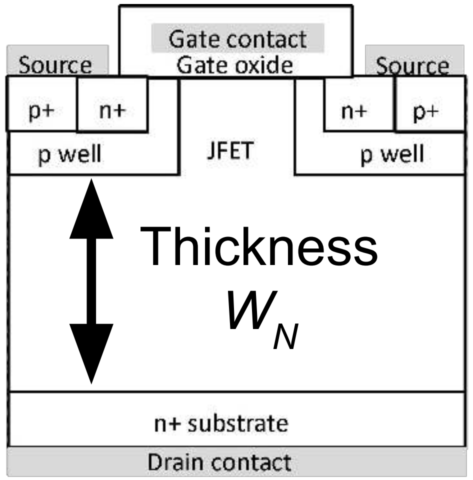


Device Thickness

$$W_N = \left(\frac{3}{2}\right)\left(\frac{V_B}{E_C}\right)$$

Device Resistance

$$R_{ON,SP} = \left(\frac{3}{2}\right)^3 \frac{V_B^2}{\mu_N \varepsilon_S E_C^3}$$



Large Bandgap and Critical Electric Field allow for high voltage devices with thinner layers: lower resistance and associated conduction losses

Thinner layer and low specific on-resistance allow for smaller form factor that reduces capacitance: higher frequency operation, reduced size passives

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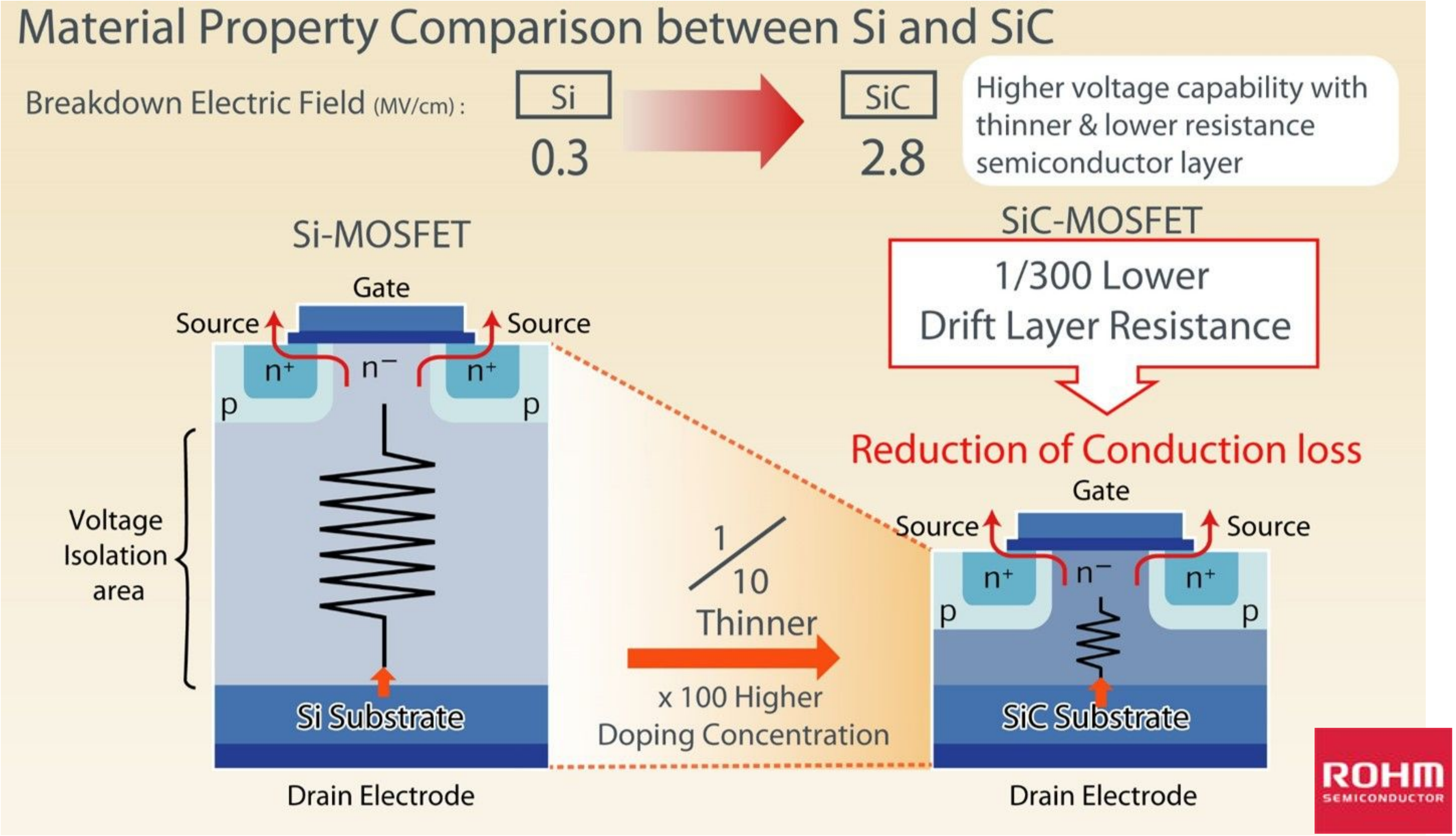
Large SiC Bandgap and Critical Electric Field Enable Low Conduction Losses and High Frequency



Aly Mashaly *et al.*, https://www.rohm.de/electronics-basics/sic/what-are-sic-semiconductors

Large SiC Bandgap and Thermal Conductivity Enable Robust High Temperature Operation with Reduced Cooling

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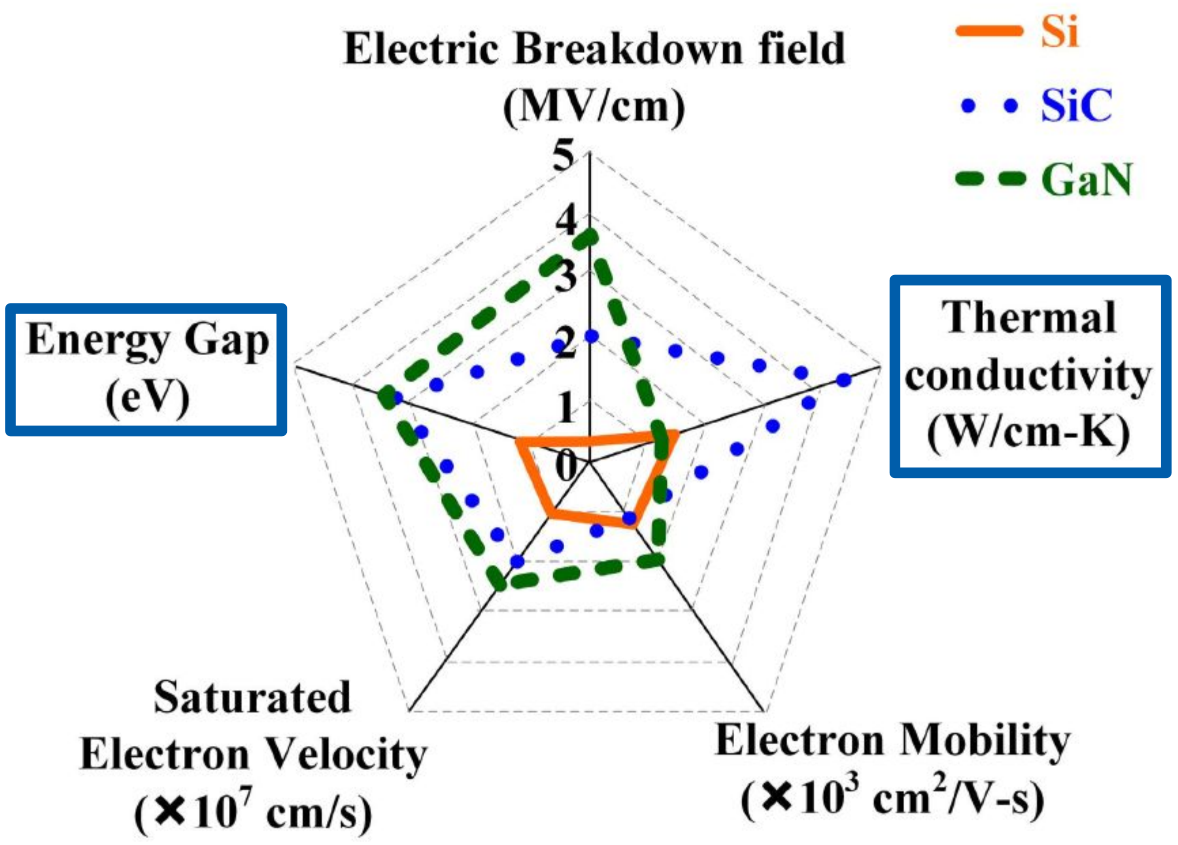

SiC/GaN devices enable **more efficient, lighter, smaller form factor** power electronics operating at high frequencies, and at elevated temperatures with reduced cooling.

Large Bandgap results in relatively low intrinsic carrier concentration: low leakage and robust high temperature operation

Large Thermal Conductivity: high power operation with reduced cooling requirements

SiC/GaN Devices Are Uniquely Positioned to Enable Next Generation Power Electronics Growth

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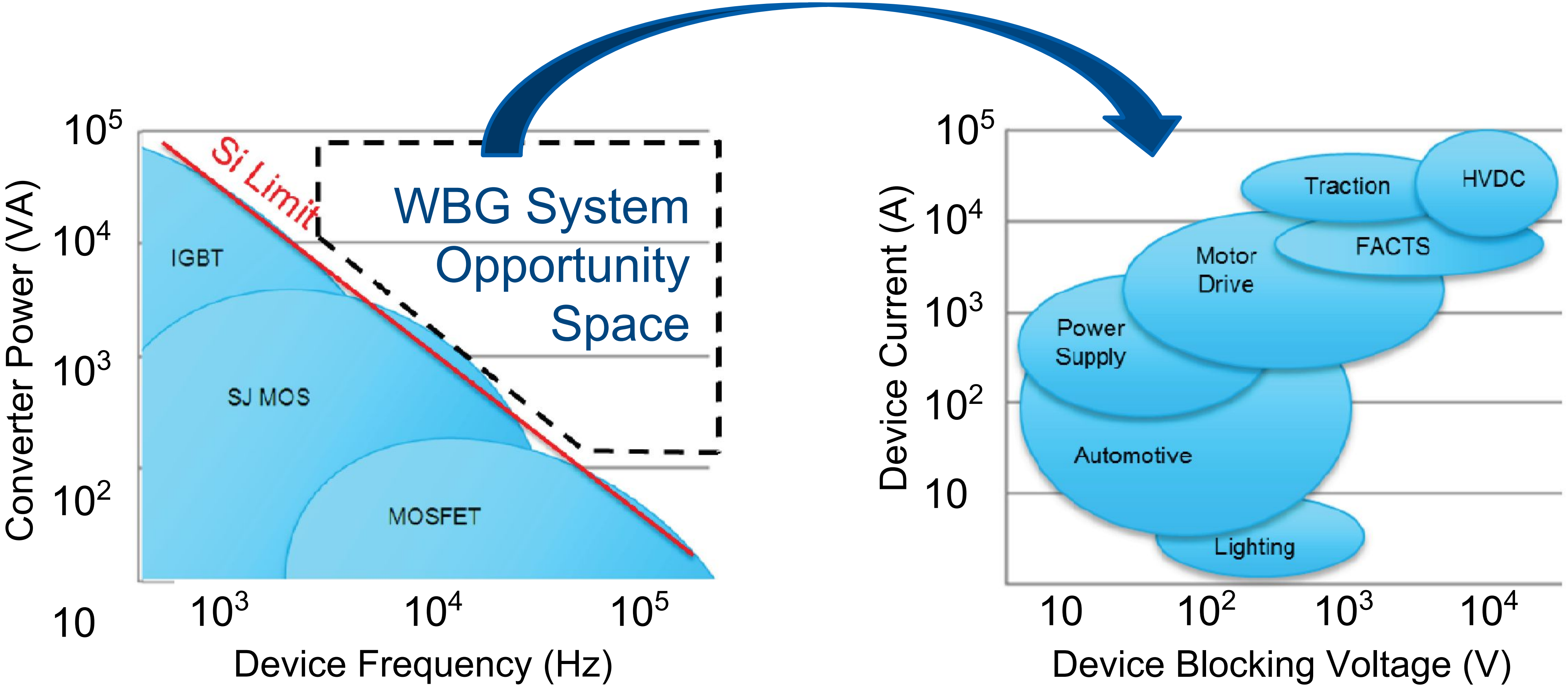

Graphs: Isic C. Kizilyalli *et al.*, ARPA-e Report 2018
https://arpa-e.energy.gov/sites/default/files/documents/files/ARPA-E_Power_Electronics_Paper-April2018.pdf

Electronics is the Foundation of High-Value Manufactured Products and Power Electronics is a Key Driver

PowerAmerica

Aerospace Sector
Global Market: US$700B
U.S. Exports: at US$120B is the largest US export market
Power Electronics Drivers: Sensors/Radar, Actuation, Propulsion

Automotive/Transportation Sector
2nd largest U.S. export market
Power Electronics Drivers: Vehicle Electrification & Automation

Grid Infrastructure Sector
Power Electronics Drivers: Reliability, Sustainability, Flexible Resources

Electric Motor Drives
Power Electronics Drivers: Variable Speed Drives, Efficiency, Weight & Volume reduction

Information Technology Hardware Sector
Power Electronics Drivers: Efficiency & Bandwidth Growth

"More Electric Aerospace" is Primarily an Evolutionary Application of Power Electronics and Energy Storage

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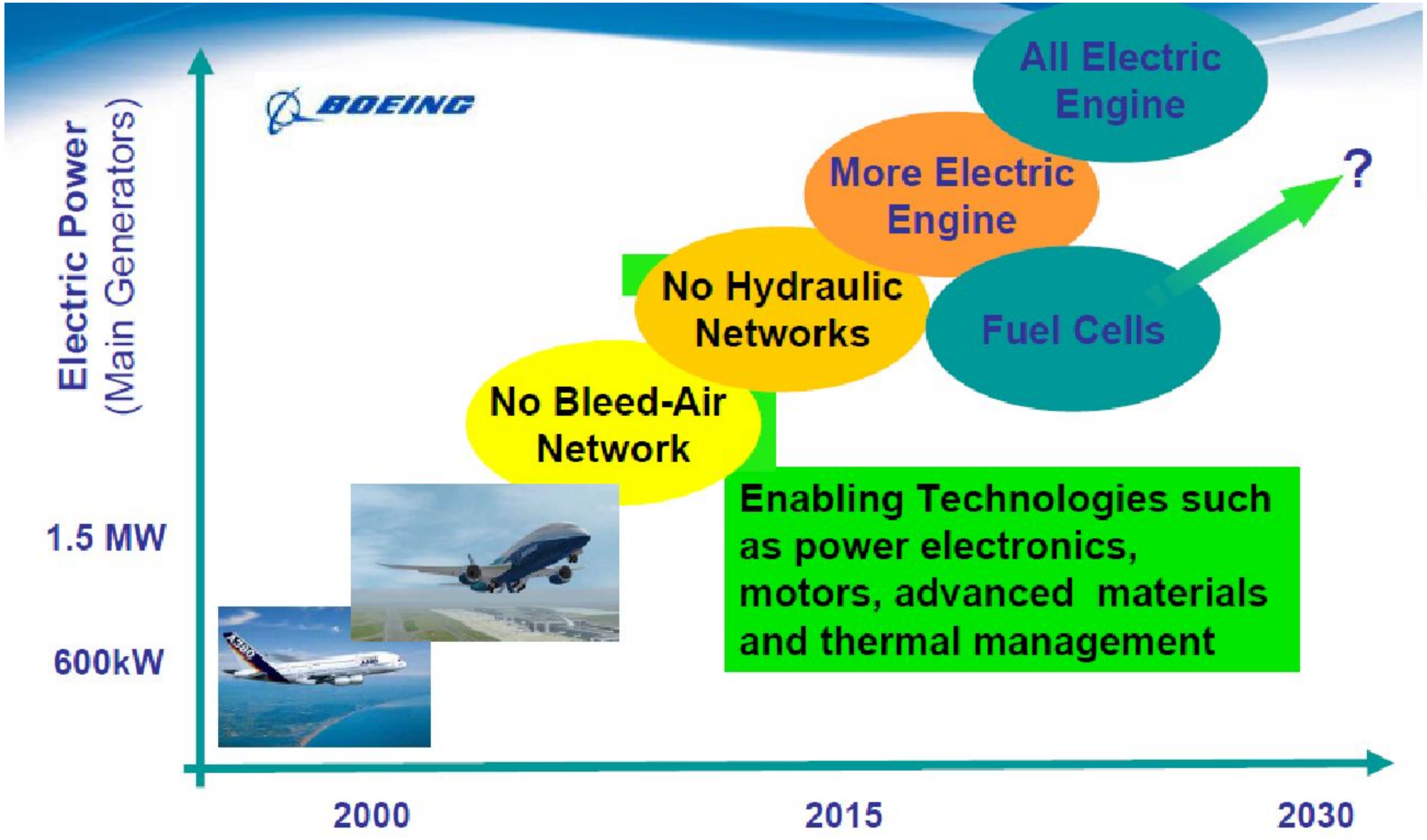
A more electric aircraft is a more energy efficient aircraft

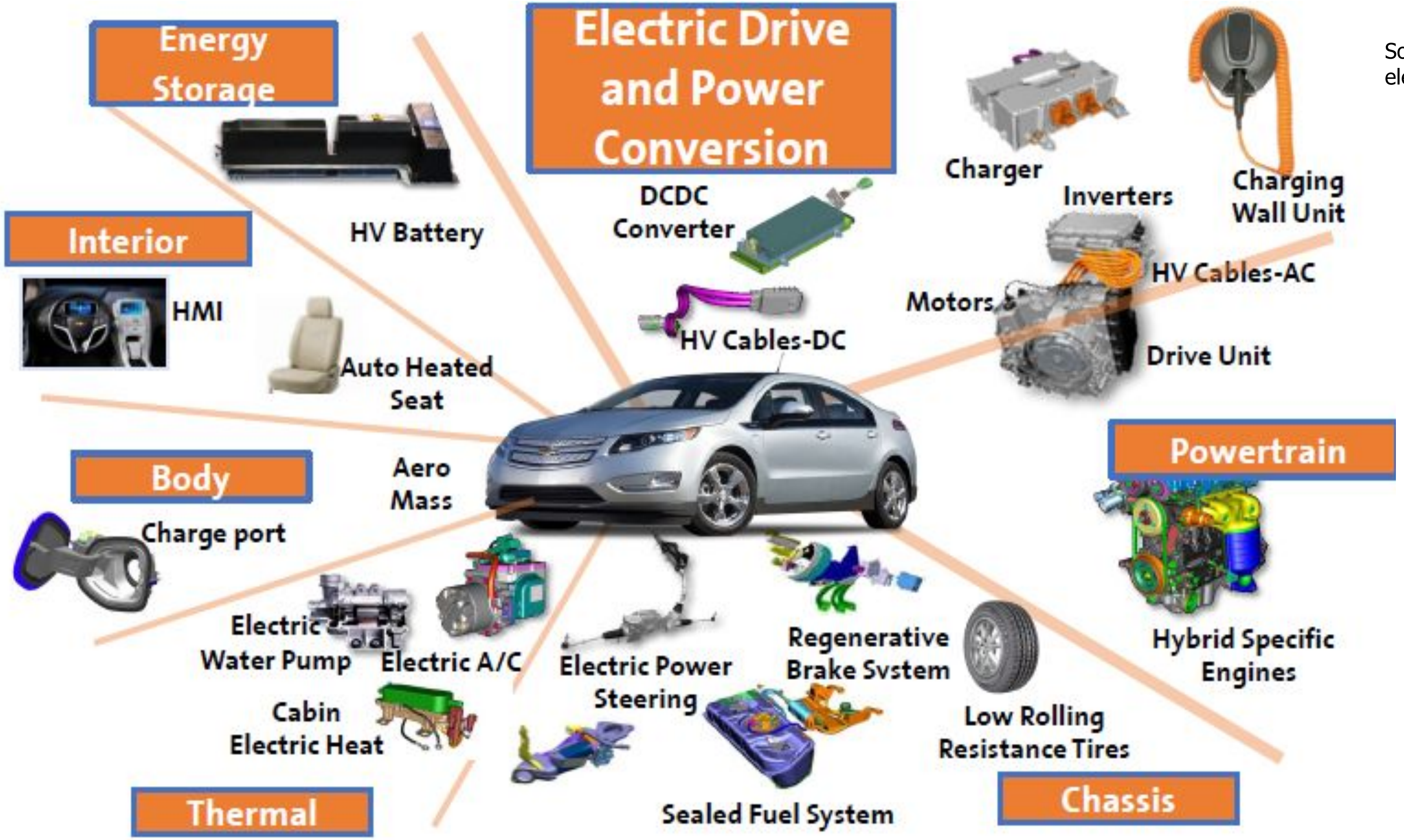


Power electronics innovations drive aerospace – aircraft, satellites, drones, rovers

- *Replace hydraulic systems with electrical*: lower fluid leak hazard, lower operation/maintenance cost, lower system complexity, higher reliability
- *Electrical generation/distribution systems replace electromechanical relays, pneumatics, and hydraulics*: reduce aircraft wiring and overall weight for fuel savings
- *Increased power electronics density*: reduces aircraft weight for fuel savings

Better fuel efficiency, lower maintenance/operation costs, higher reliability, less noise, lower NOx emissions

Power Electronics is Increasingly Prevalent in Hybrid/Electric Vehicles

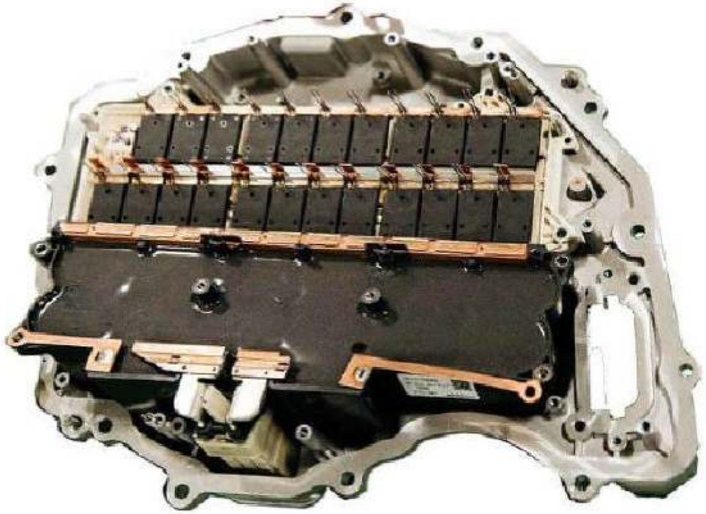


Source: SDRIVE, "Electrical and electronics technical team roadmap"

In 2014 >25% of all energy usage in the U.S. was consumed in transportation, 98% of that came from fossil fuels

Electric/Hybrid Vehicle Adoption of SiC Power Electronics is Happening Now

- Tesla Model 3 main inverter, features 24 SiC MOSFET modules from ST Microelectronics



https://www.pntpower.com/tesla-model-3-powered-by-st-microelectronics-sic-mosfets/

- 2014, Toyota, in collaboration with Denso, introduced a prototype SiC power control unit for its Prius HEV, which demonstrated a 5% improvement in the fuel economy over the standard JC08 Japanese drive cycle
  http://newsroom.toyota.co.jp/en/detail/2656842

- Review of the WBG devices and their adoption in EVs and HEVs:
  D. Han, S. Li, W. Lee and B. Sarlioglu, "Adoption of wide bandgap technology in hybrid/electric vehicles-opportunities and challenges," in *Proc. IEEE Transportation Electrific. Conf. Expo (ITEC)*, Chicago, IL, 2017, pp. 561-566

Advances in Power Electronics and Control Systems Drive Efficient, Flexible, and Reliable Grid

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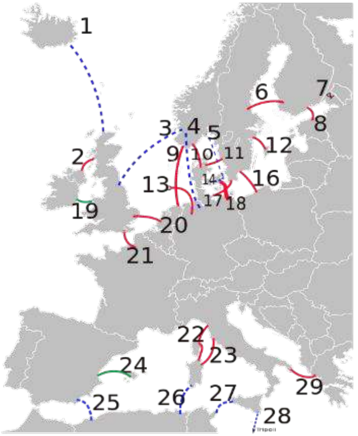
Electric Grid Applications

- HVDC Interface
- FACTS
- Microgrids
- Solar Interface
- Wind Interface
  (500 GW installed)
- Energy Storage Interface



Currently, ~40% of generated electric power passes through Power Electronics between generation and use

Variable Speed Drives Enable Efficient Adaptation to Motor Speed/Torque and Reduce Energy Consumption



Traditional Motor Drives: 20-40% of energy is wasted with throttles and other mechanical devices

13.8 kV
3 phase
60 Hz

Big
60 Hz
Transformer

4.16 kV
3 phase
60 Hz

→

1-50 MW
60 Hz
Motor

→

Gear Box

→

Compressor
Fixed Speed

Across all sectors, electric motors account for approximately 40% of total U.S. electricity demand

https://arpa-e.energy.gov/sites/default/files/documents/files/ARPA-E_Power_Electronics_Paper-April2018.pdf

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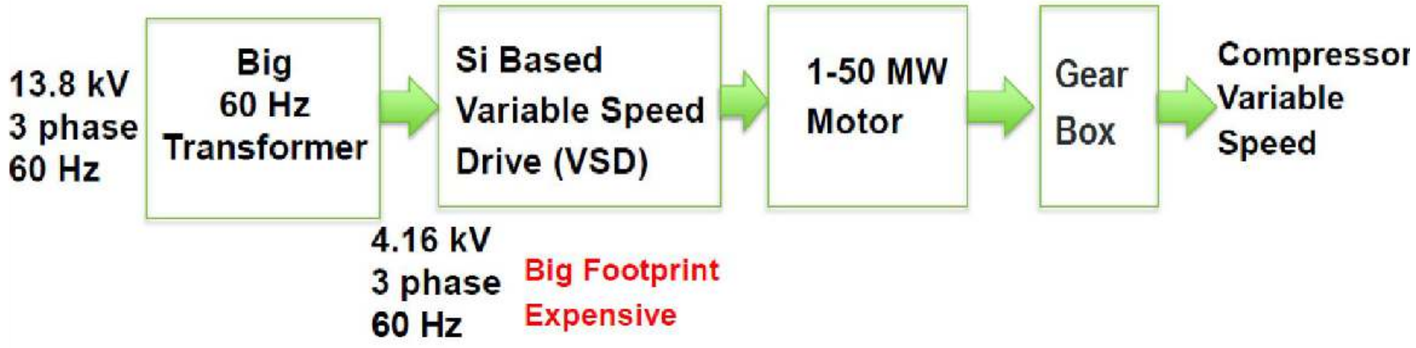
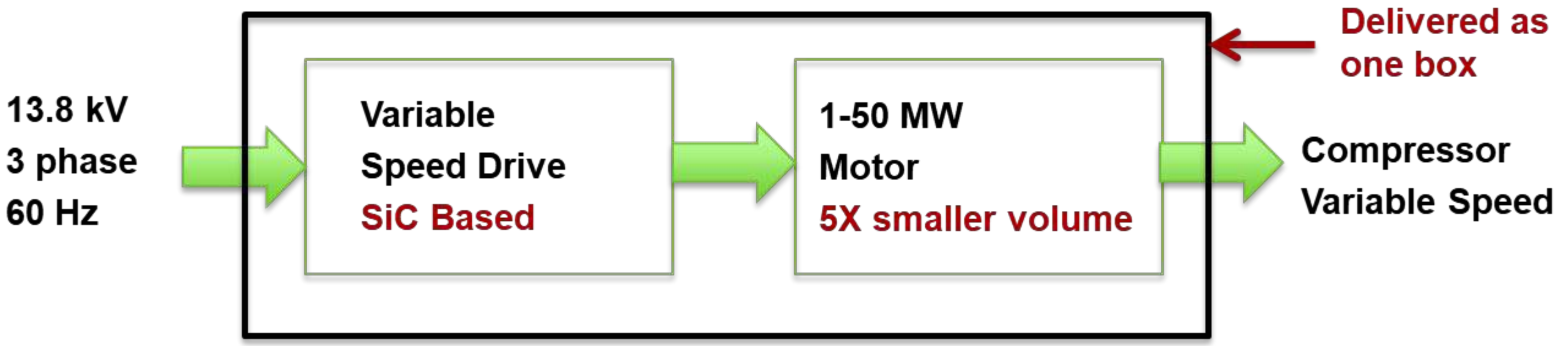
SiC Based Variable Speed Drives have Volume, Weight, and Cost Advantages

Si based VSD save energy but have limited adoption due to big footprint, weight, and cost



SiC based VSD use novel architectures to reduce volume, weight and cost, accelerating adoption



- Big 60 Hz Transformer replaced by small high frequency Transformer
- VSD system is reduced in size & weight and cheaper due to WBG devices
- Gear Box eliminated
- Motor size reduced by 5x – cheaper, less magnets

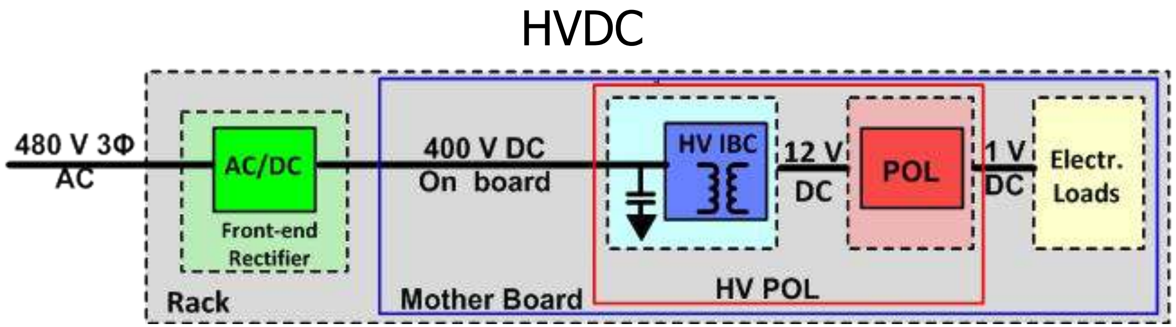
US Department of Energy (DOE), Next Generation of Electric Machines Program

The Range International Information Group Data Center in Langfang China is 6.3 Million Square Feet in Area

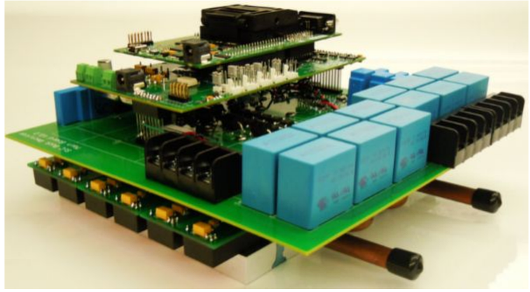
Waste Heat Management is Challenging!

Data Center power consumption is projected to reach 10% of the total electrical power consumption by 2020

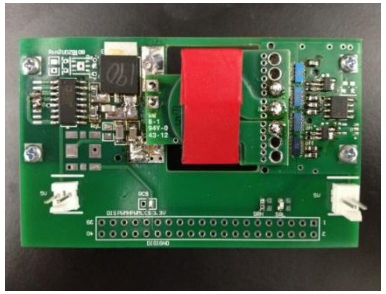
Efficient Data Center Architectures are Enabled by SiC/GaN Power Electronics Innovations



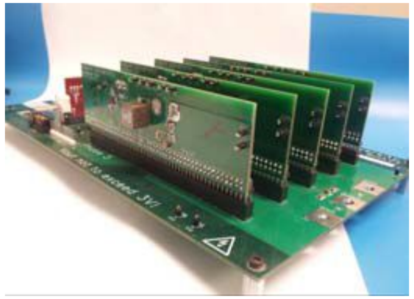
Full Load Efficiency: 98.5% × 96.1% × 94.0% = 89.0%



Front end rectifier:
7.5 kW, 480 Vac to 400 Vdc
SiC devices



HV IBC:
300 W, 400 V to 12 V
GaN devices



POL:
200 W, 12 V to 1 V
GaN devices

HV POL:
400 V to 1 V

SiC/GaN Power Electronics simplify data center waste heat management

Figures courtesy of Dr. Leon M. Tolbert

PowerAmerica is Accelerating Adoption of WBG Power Electronics

- The U.S Department of Energy launched the PowerAmerica Manufacturing Institute to Accelerate Adoption of Wide Band Gap power electronics.
- PowerAmerica started operations in 2015 with $140M funds over 5 years, and is managed by North Carolina State University in Raleigh, NC USA.
- PowerAmerica addresses gaps in WBG power technology to enable <u>US manufacturing job creation</u> and <u>energy savings.</u>

PowerAmerica is Member Driven and Active in **All Areas** of the Power GaN-SiC Supply Chain

PowerAmerica

SiC Foundry

Wolfspeed
X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

SiC Devices Circuits & Modules

USCi United Silicon Carbide, inc.
Wolfspeed
GeneSiC SEMICONDUCTOR
Sonrisa Research, Inc. Creating Progress Through Revolutionary Innovation
ON Semiconductor
MONOLITH SEMICONDUCTOR INC.
Microsemi Power Matters.
GlobalPower TechnologiesGroup
GE

GaN Devices & Circuits

Navitas SEMICONDUCTOR
Infineon
HELLA

WBG Systems

GM
TOSHIBA
Raytheon
ATOM POWER
JENOPTIK
BAE SYSTEMS
ABB
JOHN DEERE
United Technologies Research Center
GE
LOCKHEED MARTIN

Academic

Texas Tech
UC DAVIS UNIVERSITY OF CALIFORNIA
UCSB UNIVERSITY OF CALIFORNIA SANTA BARBARA
AUBURN UNIVERSITY
VirginiaTech
Kettering University
Georgia Tech Center for Distributed Energy
M DEARBORN
UNC CHARLOTTE
San José State University 1857
Arizona State University
The Florida State University 1851
NC STATE UNIVERSITY
Rensselaer
The Ohio State University
The University of Akron
The University of Tennessee Knoxville
SUNY Polytechnic Institute
Alabama
University of Colorado Boulder

Gov. Labs

Naval Research Laboratory Washington, DC
Argonne NATIONAL LABORATORY
Sandia
NREL NATIONAL RENEWABLE ENERGY LABORATORY

Consortia

PEIC POWER ELECTRONICS INDUSTRY COLLABORATIVE
iNEMI Advancing manufacturing technology

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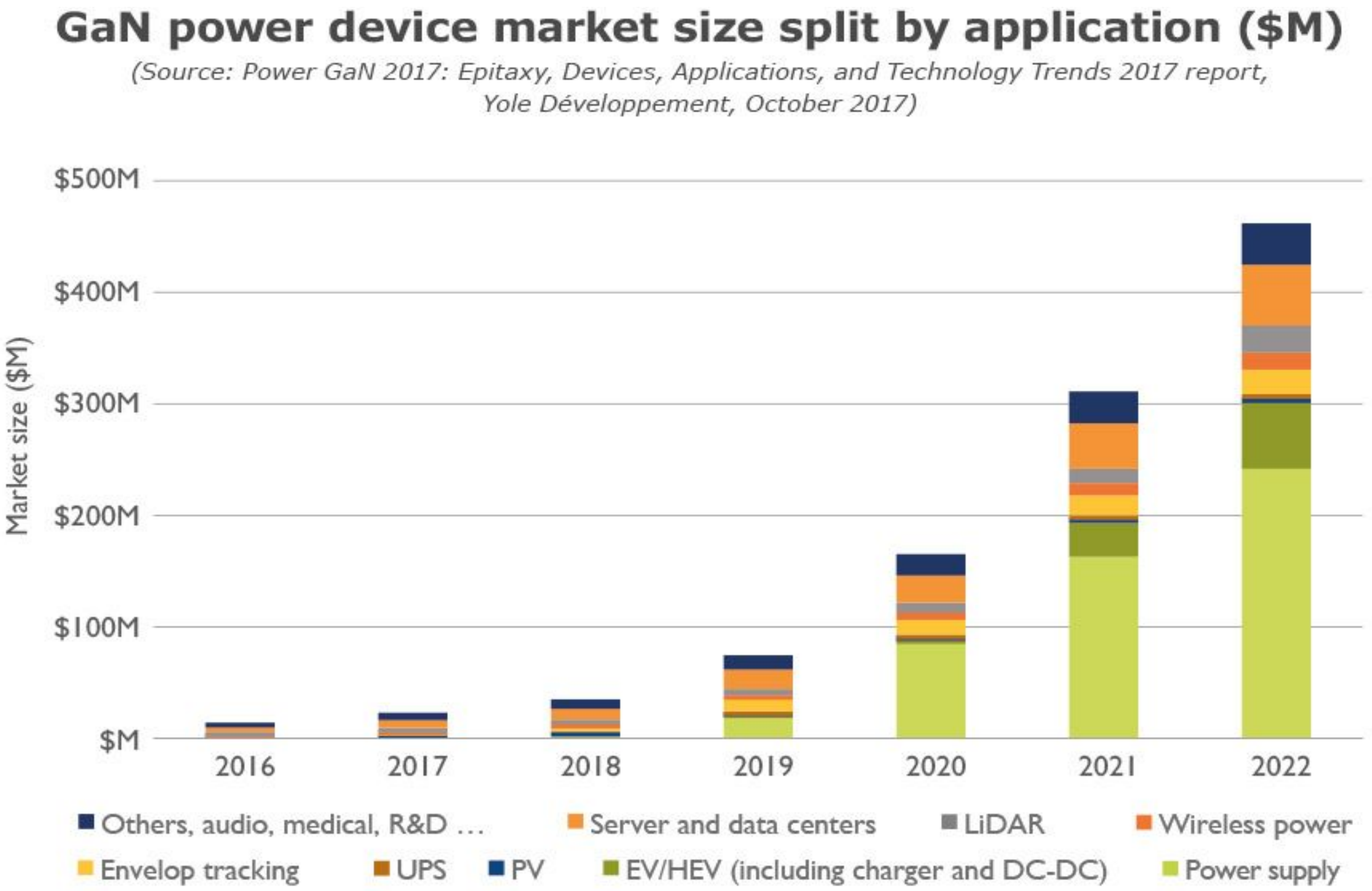
GaN Device Projected Revenue by 2022: $450M/Yr



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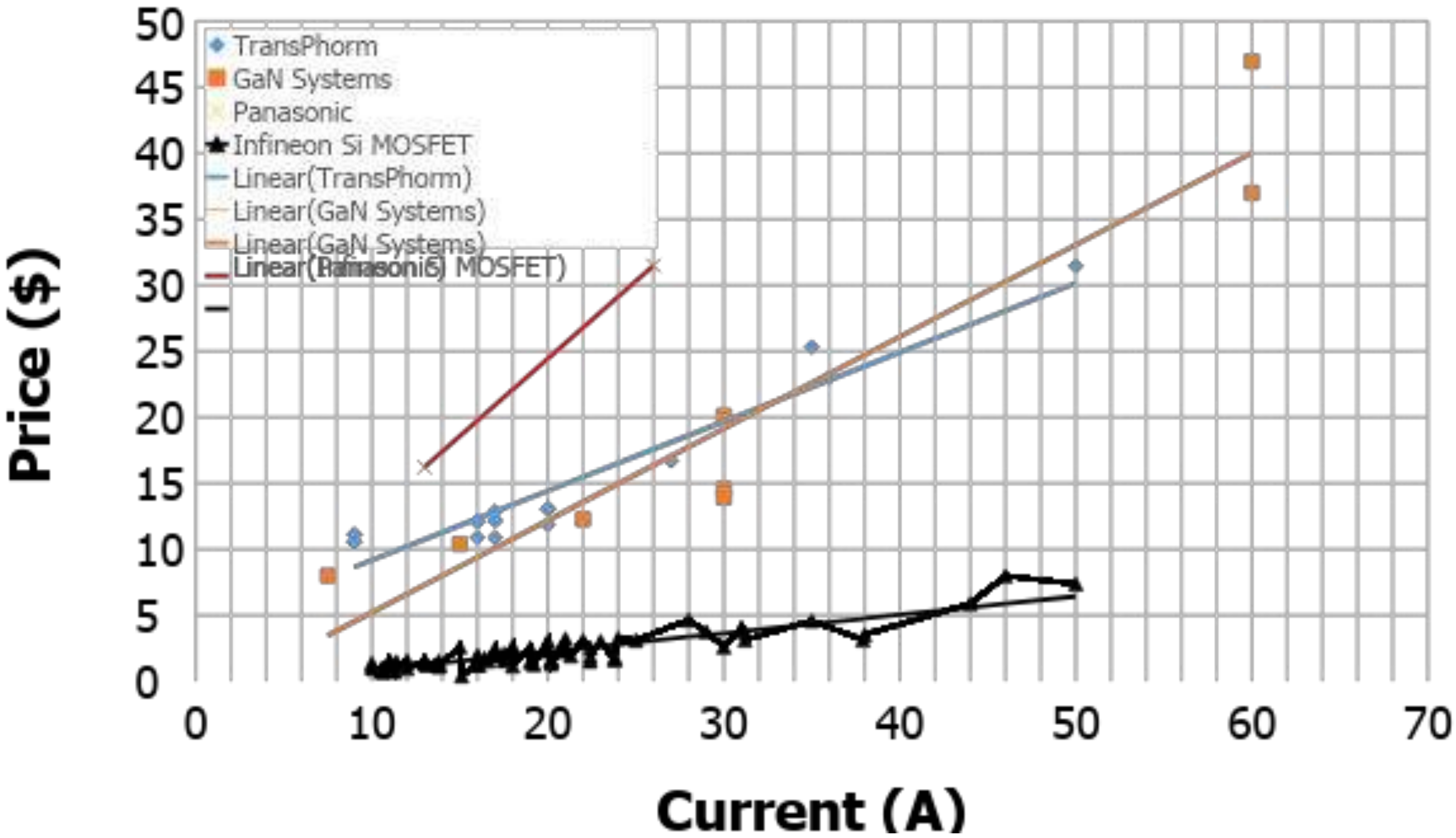
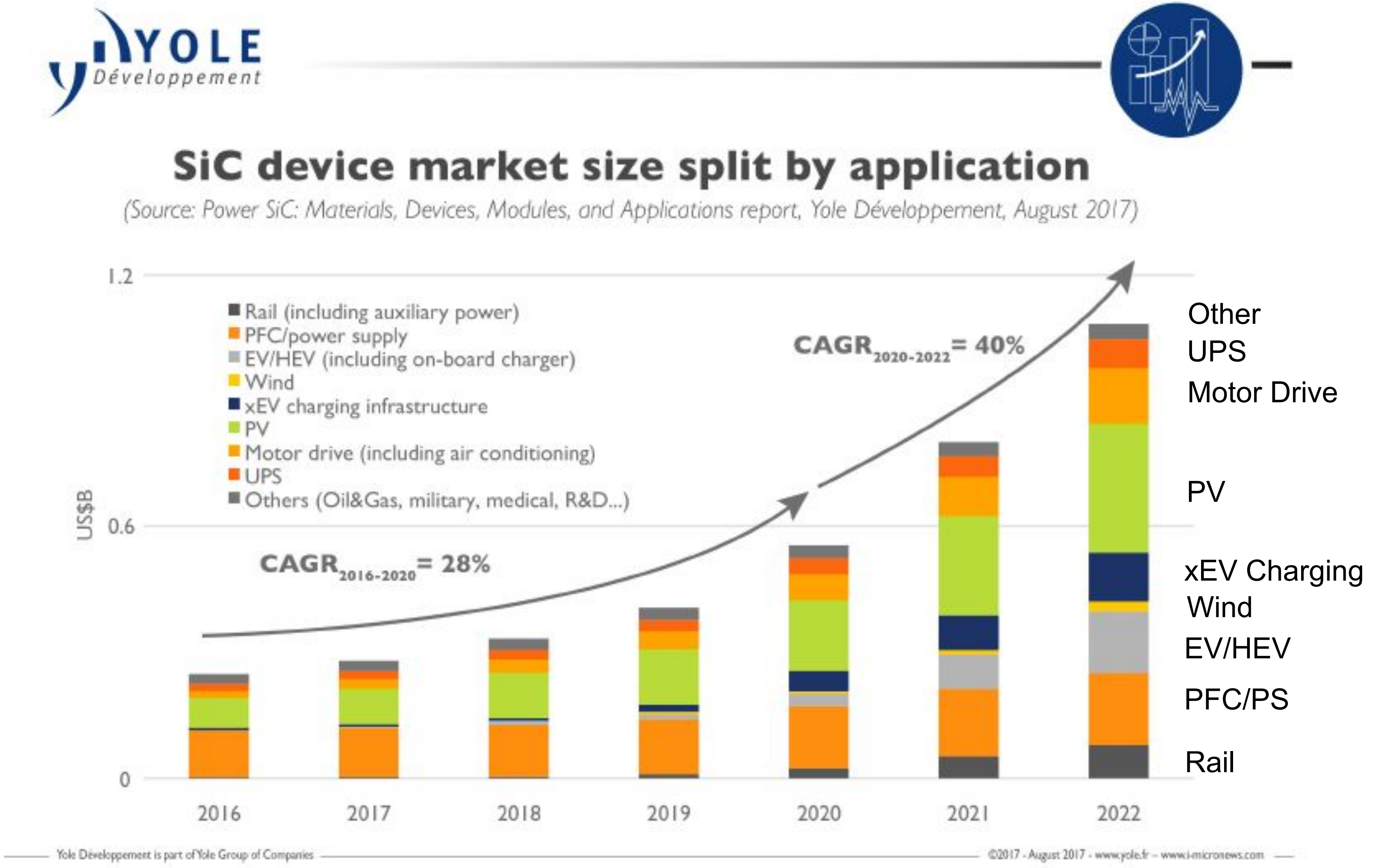
600-V Lateral GaN Power Transistors Are More Expensive than Similarly Rated Si Devices



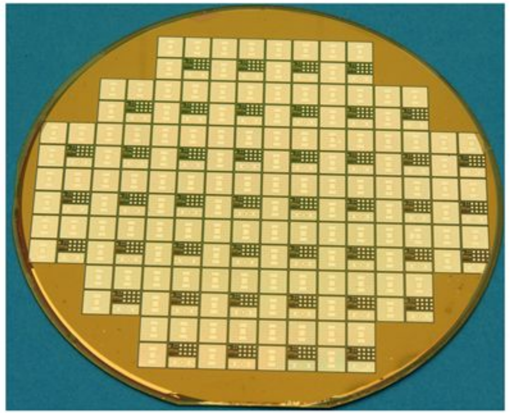
Price parity can be achieved at the system level due to reduced size and weight of magnetics, and reduced system cooling requirements. Reduced system losses provide savings throughout life of the system.

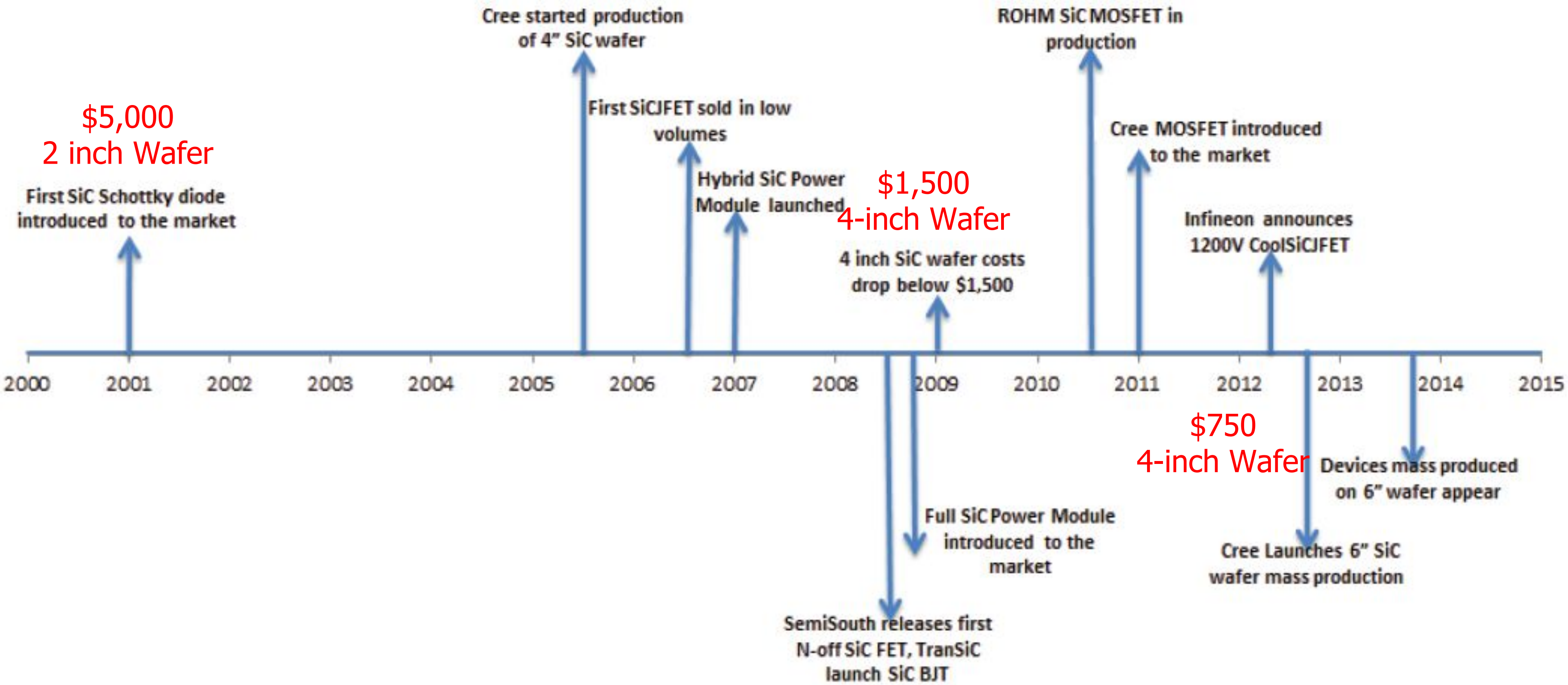
SiC Device Revenue by 2023: $1.5B/Yr



SiC Wafer Cost Lowers with Volume Production and Technological Improvements

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

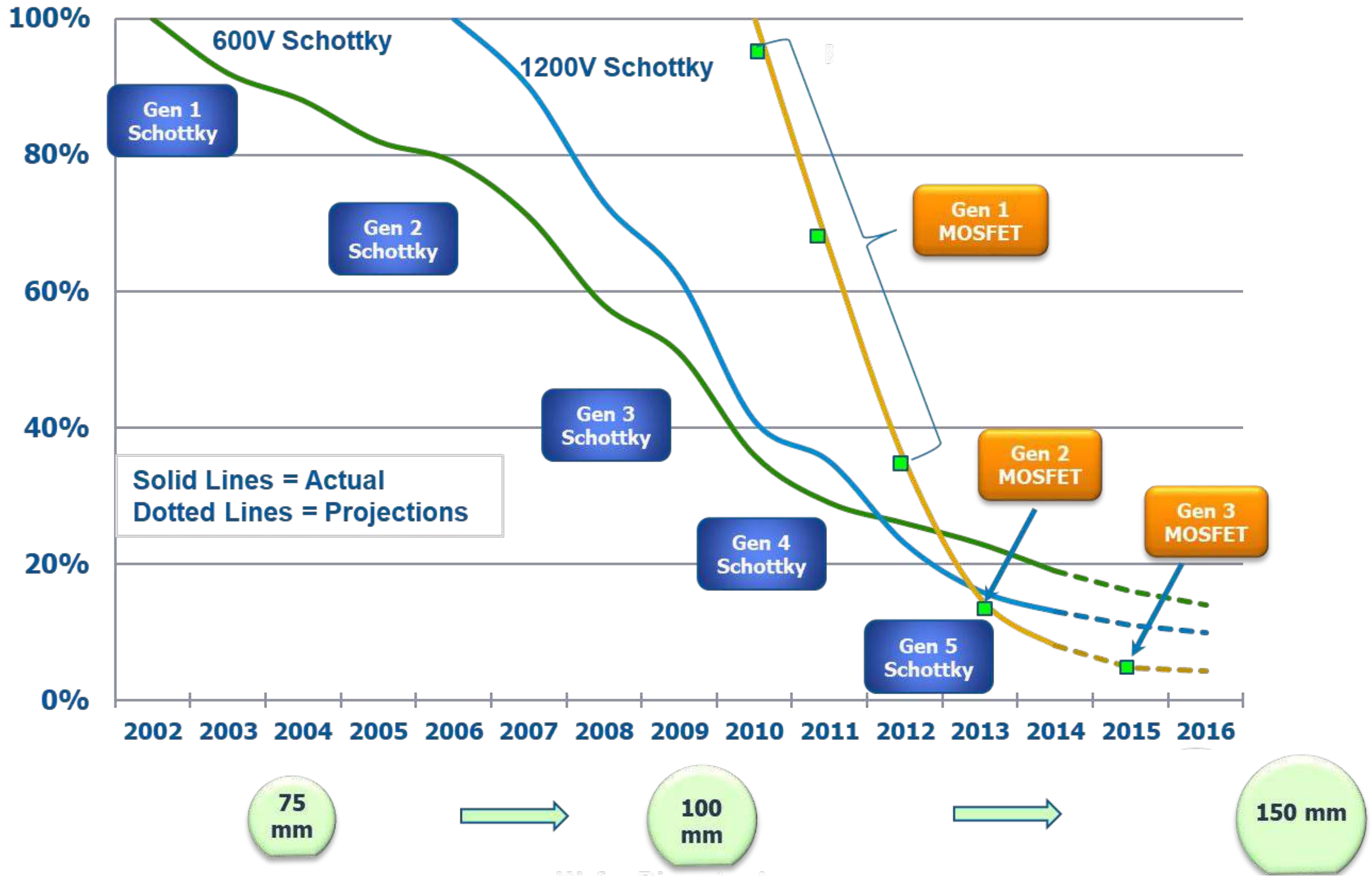




Manufacturing volume lowers wafer costs. Larger area wafer lowers device cost.

Manufacturing Volume, Larger Wafer Area, and Technological Innovations Drive SiC Device Cost Reductions

Graph: Wolfspeed, 2014



Normalized area: 1 1.8 4

1200-V SiC MOSFETs Are More Expensive Than Similarly Rated Si Devices

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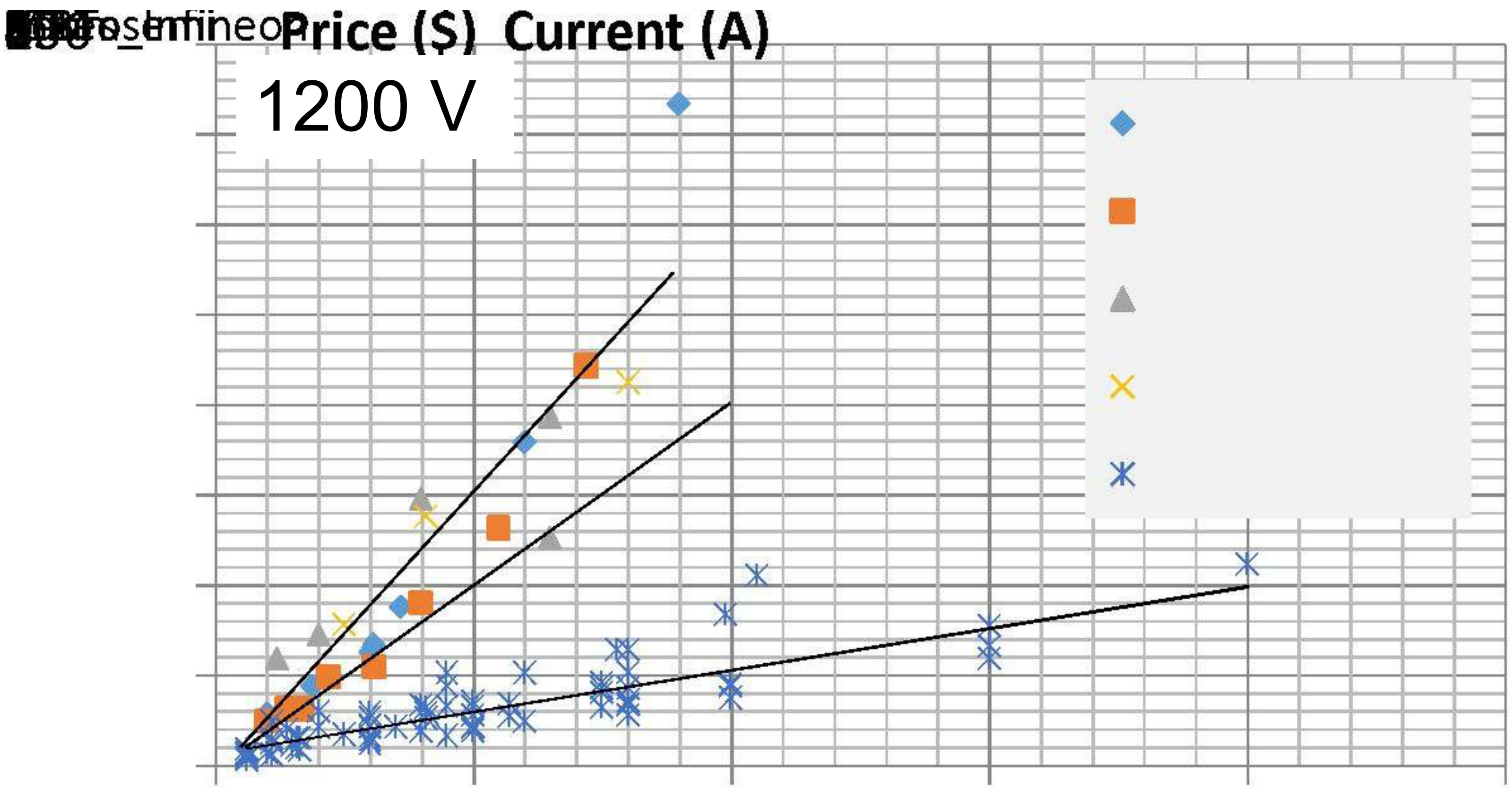
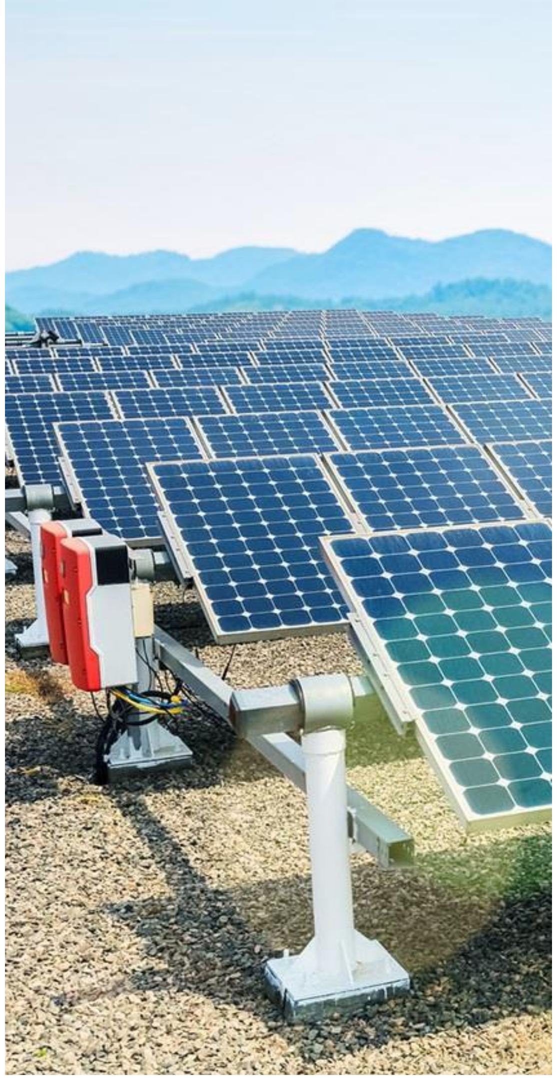


www.digikey.com, Oct. 2017

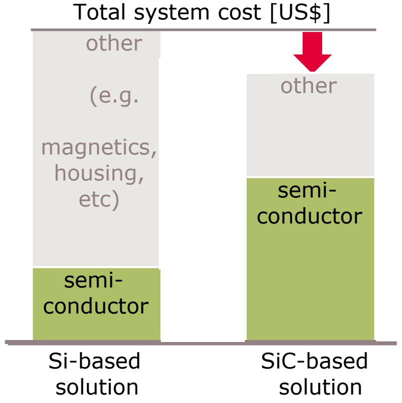
Price parity can be achieved at the ***system level*** *due to reduced size and weight of magnetics, and reduced system cooling requirements. Reduced system losses provide savings throughout life of the system.*

SiC MOSFETs Can Reduce System Cost (and Size) Despite Their Higher Than Si Price



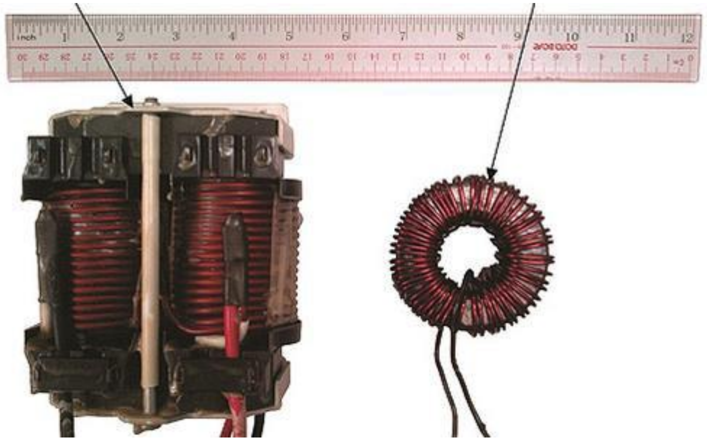
PV Reduction of system cost and size with SiC

- 10-15% lower BOM
- 2-3x higher semiconductor costs



100KHz

20KHz



At 5kW Power

Courtesy:
Dr. Levett, Infineon

SiC Wafer Demand Explodes in Anticipation of High Volume Adoption

PowerAmerica

- Cree, Inc. Announces Long-Term Silicon Carbide Wafer Supply Agreement with Infineon

2/26/2018

The agreement governs Cree's supply of advanced **150 mm SiC wafers** to Infineon, valued at well over **$100 million**.

https://www.wolfspeed.com/news/cree-inc-announces-long-term-silicon-carbide-wafer-supply-agreement-with-infineon

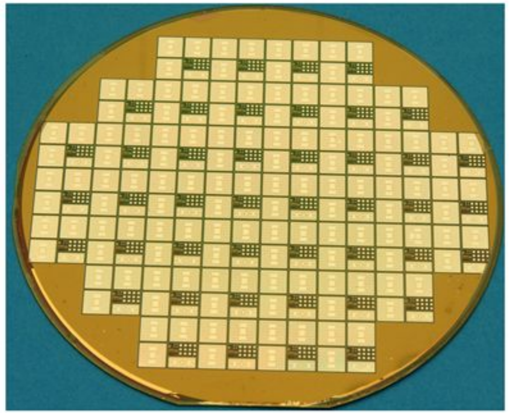
- Cree, Inc. (Nasdaq: CREE) announces that it signed a strategic long-term agreement to produce and supply its Wolfspeed(R) silicon carbide wafers to one of the world's leading power device companies. The agreement, valued at more than **$85 million**, governs Cree's supply of advanced 150 mm silicon carbide bare and epitaxial wafers, 10/16/18

  https://www.cree.com/news-events/news/article/cree-announces-long-term-silicon-carbide-wafer-supply-agreement-with-leading-global-semiconductor-company

- Cree and STMicroelectronics Announce Multi-Year Silicon Carbide Wafer Supply Agreement, 1/7/2019

The agreement governs the supply of $**250 million dollars** of Cree's advanced **150mm silicon carbide** bare and epitaxial wafers to STMicroelectronics during this period of extraordinary growth and demand for silicon carbide power devices.

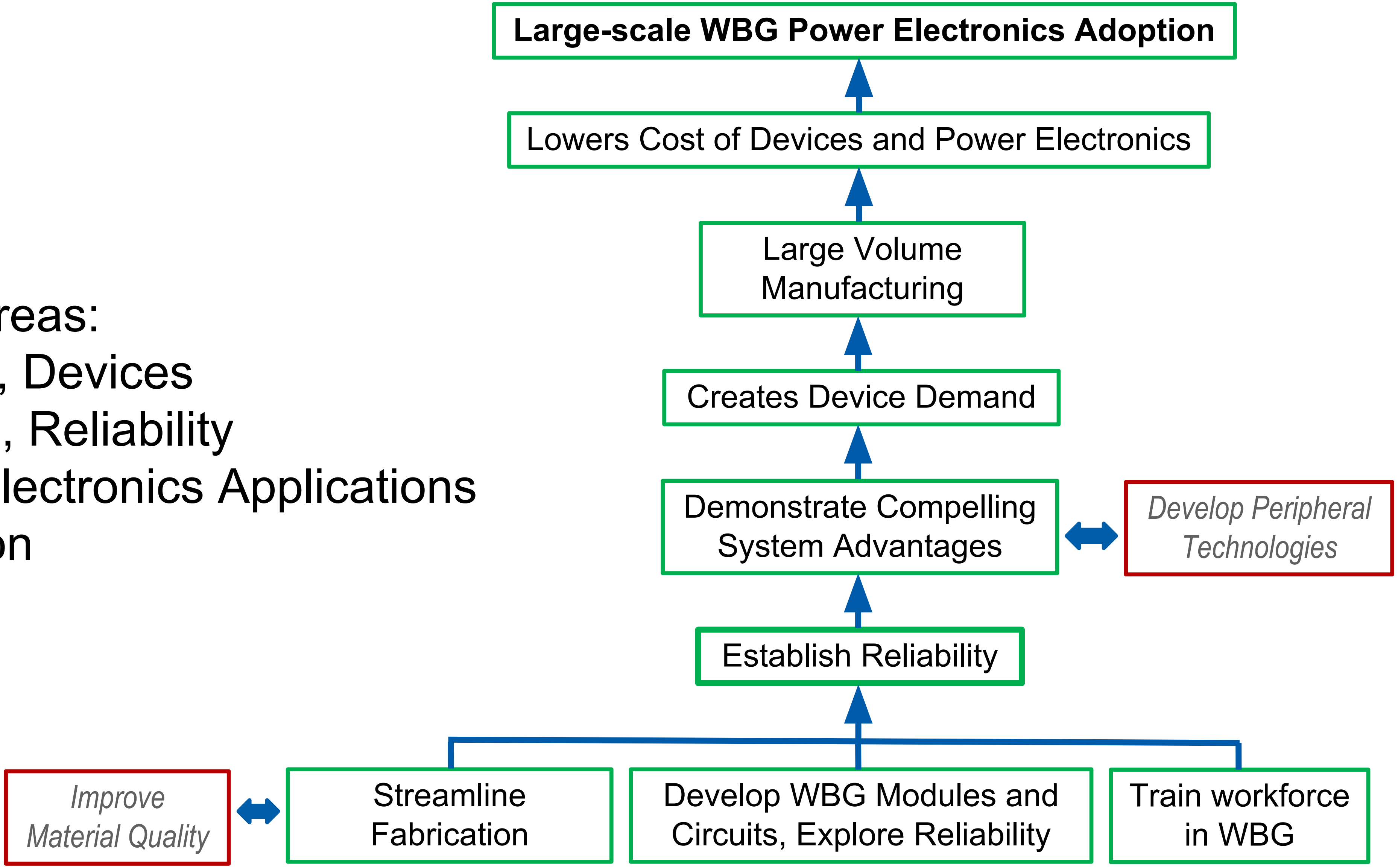
https://www.wolfspeed.com/news/cree-announces-quarter-billion-dollar-wafer-supply-agreement-with-stmicroelectronics



PowerAmerica is a Catalyst in the Manufacturing of Low Cost SiC and GaN Power Electronics

PowerAmerica

Funding Areas:
- Foundry, Devices
- Modules, Reliability
- Power Electronics Applications
- Education



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DOE/PowerAmerica Strategic Funding Allocation Accelerat
Commercialization of WBG Power Electronics

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33 NEW WBG Projects Annually
Industry/University/National-Lab

1 Management and Operations

1.1 Operations and Finance
1.2 Technology Roadmap
1.3 Sustainability
1.4 Device/Module Bank
1.6 Project Portfolio Management
1.7 Membership, Industry Relations and Communications

2 Foundry and Device Development

2.1 SiC Power Device Commercial Foundry Development **X-Fab Texas**
2.3 Development of a Manufacturable Gen3, 6.5 kV/100 mOhm MOSFET **Cree/Wolfspeed**
2.4 Commercialization of 1700V SiC Schottky Diodes **Monolith**
2.8A Lower Cost Foundry Process for 1.2 kV SiC Planar Gate Power MOSFETs and JBS Rectifiers **NCSU (Baliga)**
2.8B 1.2kV SiC Shielded Trench Gat PowerMOSFETs **NCSU (Baliga)**
2.14 3.3kV SiC MOSFET Dev **GeneSiC**
2.20 1.7kV/3.3kV SiC M up **Microsemi**
2.21A Developm 3.3kV/6.5kV/1 Diodes, ar MOSFE
2.2
...
ve, SFETs
MHz DC-DC Circuit ***Ricketts -***

3 Module Development & Manufacturing

3.1 High Voltage 6.5kV 10 kV Power Module Commercializatio Manufacturing **Fayettevill**
3.6 Dev Free A

4 Co A

4.1
...
shiba
ith Efficiency
a Tech
verter **FSU**
d Power Conditioning
connector to MicroGrid
a)
ion 350 kW Three-Phase Medium-
fficiency EV Fast Charger **NCSU**
Active Harmonic Filter for Variable
uency Drives **UTRC + Hopkins + Husain**
.24 65W High-Efficiency, High-Density Adapter with Improved Manufacturability **Navitas**
4.25 5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules **GA Tech**
4.26 High Frequency GaN Power Converter **LMCO + VPT + VA Tech**
4.27 SiC Based Power Electronic Motor Driver for Class-8 Mild Hybrid Truck **Bendix Corporation**
4.28 Multi-functional High-efficiency High-density Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module **University of Tennessee**
4.29A *Development of Active Harmonic Filter using Interleaved SiC Inverter* ***Husain-OIF***
4.29B *Modeling and Packaging Design of a High Power Density 150A SiC Inverter* ***Hopkins-OIF***
4.30 *High Power Density DC-DC Converter for Auxiliary Power in Heavy-Duty Vehicles* ***Bhattacharya-OIF***
4.31 *A High-efficiency Low-cost 22kW Fast On-board Charger for Electric Vehicles Using Hybrid Switches Combining GaN HEMTs with Si MOSFETs* ***Hella-OIF***

5 ucation and orkforce Development

5.1 Education and Workforce Pipeline Development
5.4 Undergraduate Research Scholars
5.5 Pre-College Education **5.6** WBG Short Courses
5.13 Documentation of Design and Process of GaN Power HEMTs **RPI**

PowerAmerica Foundry Projects Enable Low-Cost Large Volume SiC Device Manufacturing in the U.S.

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1 Management and Operations

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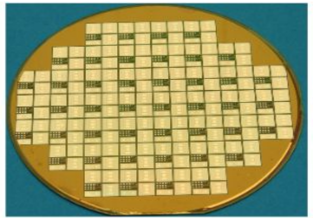

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2.14 3.3kV SiC MOSFET Development **GeneSiC**
2.20 1.7kV/3.3kV SiC MOSFET Scale-up **Microsemi**
2.21A Development of 3.3kV/6.5kV/10kV SiC MOSFETs, JBS Diodes, and JBS Diode Integrated MOSFETs **SUNY**
2.21B Development of 600V SiC JBS Diodes and MOSFETs **SUNY**
2.23 Advanced SiC Trench MOSFETs: A Path to Record-Low Ron,sp and Record-Low ($/A) **Sonrisa Research**
2.24 Manufacturable, Cost Effective, Low RON-SP 3.3 kV SiC DMOSFETs **Global Power**
2.25** 50 W GaN 15 -100 MHz DC-DC Converter Integrated Circuit **Ricketts - OIF

3 Module Development & Manufacturing

3.1 High Voltage 6.5kV & 10 kV Power Module Commercialization and Manufacturing **Cree Fayetteville**
3.6 Developing a BPD-Free Room Temperature Al Implant and Activation Anneal Process for P-Wells in SiC MOSFETs **NRL**
3.7 Reliability Analysis of Wide Band Gap Power Devices **Texas Tech**
3.8** 100A, 6.5KV Half-Bridge Module **USCI

4 Commercialization Applications

4.1 Design, Fabrication, and Vehicular Testing of SiC Inverter for Heavy-Duty Vehicles **John Deere Electronic Solutions**
4.3 SiC Device based Commercial Hybrid PV Inverter with Li-ion Battery Integration **Toshiba**
4.7 100 kW Commercial PV Inverter with Efficiency > 99 % Operating in iTCM **Virginia Tech**
4.10 100 kW Commercial PV Inverter **FSU**
4.11 Asynchronous Microgrid Power Conditioning System (Microgrid PCS) connector to MicroGrid **NCSU (Bhattacharya)**
4.13 Next Generation 350 kW Three-Phase Medium-Voltage High-Efficiency EV Fast Charger **NCSU (Lukic)**
4.23 SiC Active Harmonic Filter for Variable Frequency Drives **UTRC + Hopkins + Husain**
4.24 65W High-Efficiency, High-Density Adapter with Improved Manufacturability **Navitas**
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PowerAmerica Supports U.S. SiC Foundry Infrastructure

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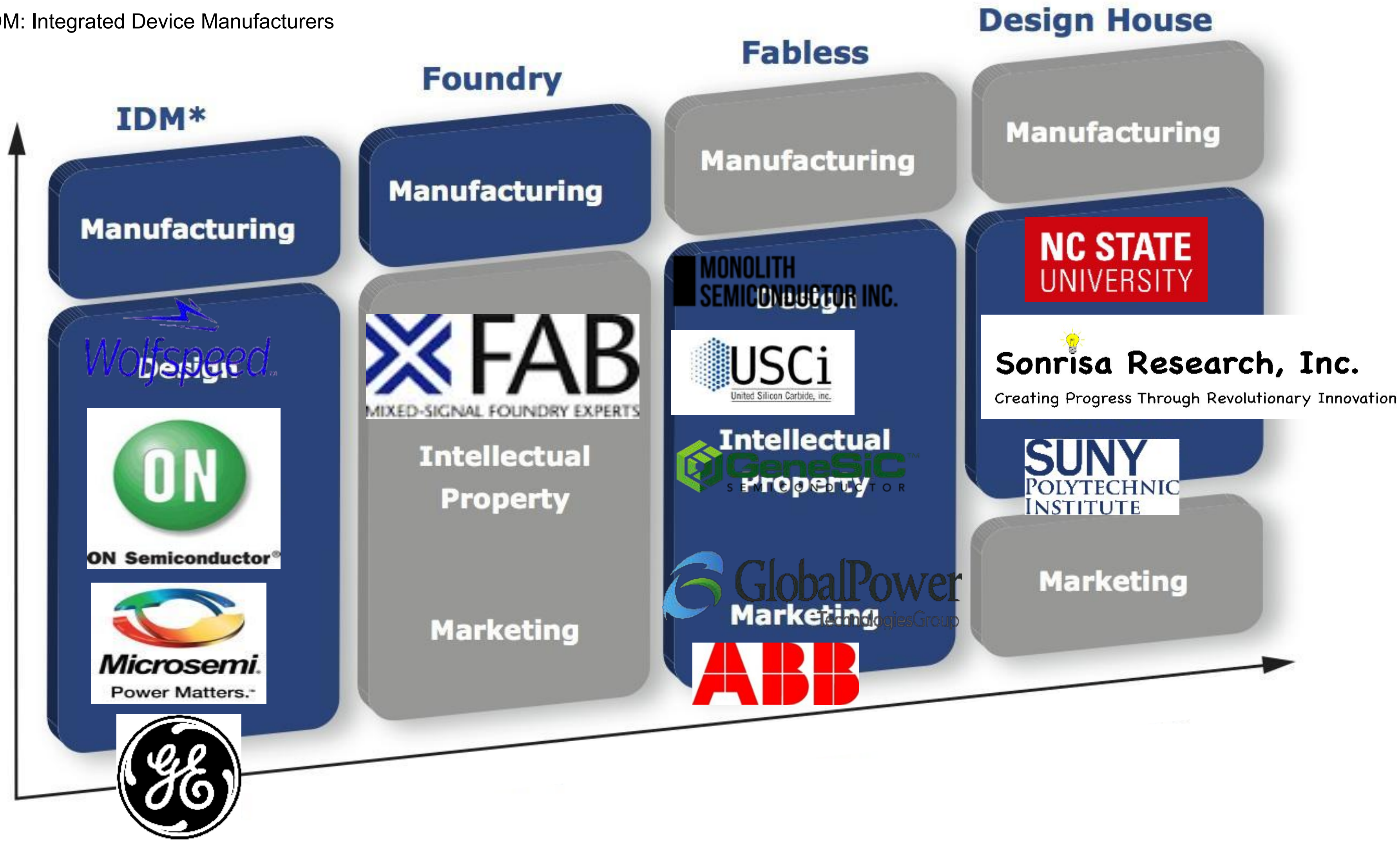
*IDM: Integrated Device Manufacturers



SiC Foundry
- Wafer quality/supply
- Compete on Processing

(source: Successful Semiconductor Fabless conference, Yole Développement, Mar. 2013)

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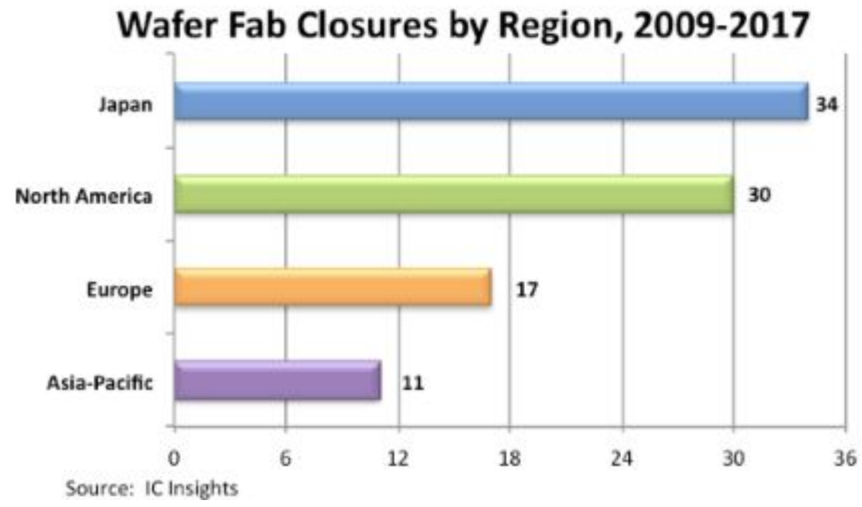
X-FAB 150-mm SiC Open Foundry Leverages Existing Si Economy of Scale to Reduce SiC Manufacturing Cost

X-FAB/PowerAmerica Manufacturing Vision

SiC Open Foundry at the Economy Scale of Silicon

- Wafer fabrication dominated by fixed O/H costs (Management, Quality, EHS, IT)
- Economies of scale is the greatest factor in reducing cost: Use the scale established in Si to enable low-cost SiC manufacturing

X-FAB 150-mm SiC open Manufacturing is fully integrated within a high volume Si foundry



X-FAB/PA SiC Users: ABB, GeneSiC, Microchip, Monolith, USCi, Global Power, Sonrisa, SUNY, and NCSU

TSMC's Low-Cost Lateral GaN Power Device Production is a Barrier to Establishing an Open Domestic GaN Foundry

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2018F Top 15 Semiconductor Sales Leaders ($M, Including Foundries)

2018F Rank	2017 Rank	Company	Headquarters	2017 Total Semi Sales ($M)	2018F Total Semi Sales ($M)	2018F/2017 % Change
1	1	Samsung	South Korea	65,882	83,258	26%
2	2	Intel	U.S.	61,720	70,154	14%
3	4	SK Hynix	South Korea	26,722	37,731	41%
4	3	TSMC (1)	Taiwan	32,163	34,209	6%
5	5	Micron	U.S.	23,920	31,806	33%
6	6	Broadcom Ltd. (2)	U.S.	17,795	18,455	4%
7	7	Qualcomm (2)	U.S.	17,029	16,481	-3%
8	9	Toshiba/Toshiba Memory	Japan	13,333	15,407	16%
9	8	TI	U.S.	13,910	14,962	8%
10	10	Nvidia (2)	U.S.	9,402	12,896	37%
11	12	ST	Europe	8,313	9,639	16%
12	15	WD/SanDisk	U.S.	7,840	9,480	21%
13	11	NXP	Europe	9,256	9,394	1%
14	13	Infineon	Europe	8,126	9,246	14%
15	14	Sony	Japan	7,891	8,042	2%
—	—	Top-15 Total		323,302	381,160	18%

(1) Foundry (2) Fabless

Source: Company reports, IC Insights' *Strategic Reviews* database

Major Pure-Play Foundry Revenue per Wafer* ($M)

Company	2017 Sales ($M)	2017 Wafer Starts (K)	2017 Revenue per Wafer	2018F Sales ($M)	2018F Wafer Starts (K)	2018F Revenue per Wafer
TSMC	$32,163	23,510	$1,368	$34,765	25,150	$1,382
GlobalFoundries	$6,176	6,125	$1,008	$6,640	6,550	$1,014
UMC	$4,898	6,837	$716	$5,165	7,225	$715
SMIC	$3,101	4,310	$719	$3,275	4,880	$671
Total/Avg.	$46,338	40,782	$1,136	$49,845	43,805	$1,138

*200mm equivalents

Source: Company reports, IC Insights

- TSMC is unmatched by any other foundry, with manufacturing capacity of over 12 million 12-inch equivalent wafers annually as of 2018
- TSMC 2018 revenue of $33.49 billion USD accounts for an enormous 48.1% market share

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Strategic **University** PowerAmerica Projects Provide Hands-on Training to the Next Generation of WBG Engineers

POWERAMERICA

1 Management and Operations

1.1 Operations and Finance
1.2 Technology Roadmap
1.3 Sustainability
1.4 Device/Module Bank
1.6 Project Portfolio Management
1.7 Membership, Industry Relations and Communications

2 Foundry and Device Development

2.1 SiC Power Device Commercial Foundry Development **X-Fab Texas**
2.3 Development of a Manufacturable Gen3, 6.5 kV/100 mOhm MOSFET **Cree/Wolfspeed**
2.4 Commercialization of 1700V SiC Schottky Diodes **Monolith**
2.8A Lower Cost Foundry Process for 1.2 kV SiC Planar Gate Power MOSFETs and JBS Rectifiers **NCSU (Baliga)**
2.8B 1.2kV SiC Shielded Trench Gate PowerMOSFETs **NCSU (Baliga)**
2.14 3.3kV SiC MOSFET Development **GeneSiC**
2.20 1.7kV/3.3kV SiC MOSFET Scale-up **Microsemi**
2.21A Development of 3.3kV/6.5kV/10kV SiC MOSFETs, JBS Diodes, and JBS Diode Integrated MOSFETs **SUNY**
2.21B Development of 600V SiC JBS Diodes and MOSFETs **SUNY**
2.23 Advanced SiC Trench MOSFETs: A Path to Record-Low Ron,sp and Record-Low ($/A) **Sonrisa Research**
2.24 Manufacturable, Cost Effective, Low RON-SP 3.3 kV SiC DMOSFETs **Global Power**
2.25** 50 W GaN 15 -100 MHz DC-DC Converter Integrated Circuit* ***Ricketts - OIF

3 Module Development & Manufacturing

3.1 High Voltage 6.5kV & 10 kV Power Module Commercialization and Manufacturing **Cree Fayetteville**
3.6 Developing a BPD-Free Room Temperature Al Implant and Activation Anneal Process for P-Wells in SiC MOSFETs **NRL**
3.7 Reliability Analysis of Wide Band Gap Power Devices **Texas Tech**
3.8** 100A, 6.5KV Half-Bridge Module* ***USCI

4 Commercialization Applications

4.1 Design, Fabrication, and Vehicular Testing of SiC Inverter for Heavy-Duty Vehicles **John Deere Electronic Solutions**
4.3 SiC Device based Commercial Hybrid PV Inverter with Li-ion Battery Integration **Toshiba**
4.7 100 kW Commercial PV Inverter with Efficiency > 99 % Operating in iTCM **Virginia Tech**
4.10 100 kW Commercial PV Inverter **FSU**
4.11 Asynchronous Microgrid Power Conditioning System (Microgrid PCS) connector to MicroGrid **NCSU (Bhattacharya)**
4.13 Next Generation 350 kW Three-Phase Medium-Voltage High-Efficiency EV Fast Charger **NCSU (Lukic)**
4.23 SiC Active Harmonic Filter for Variable Frequency Drives **UTRC + Hopkins + Husain**
4.24 65W High-Efficiency, High-Density Adapter with Improved Manufacturability **Navitas**
4.25 5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules **GA Tech**
4.26 High Frequency GaN Power Converter **LMCO + VPT + VA Tech**
4.27 SiC Based Power Electronic Motor Driver for Class-8 Mild Hybrid Truck **Bendix Corporation**
4.28 Multi-functional High-efficiency High-density Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module **University of Tennessee**
4.29A** Development of Active Harmonic Filter using Interleaved SiC Inverter* ***Husain-OIF
4.29B** Modeling and Packaging Design of a High Power Density 150A SiC Inverter* ***Hopkins-OIF
4.30** High Power Density DC-DC Converter for Auxiliary Power in Heavy-Duty Vehicles* ***Bhattacharya-OIF
4.31** A High-efficiency Low-cost 22kW Fast On-board Charger for Electric Vehicles Using Hybrid Switches Combining GaN HEMTs with Si MOSFETs* ***Hella-OIF

PowerAmerica 2016-2019

- $24M in University Projects
- 63 projects
- 300 students

19 University applied projects provide real world experience to the next generation of WBG Engineers: $6.5M, 31.5 undergrad, 42.5 grad, and 4 Post-doc full-time (FTE) trainees

V. Veliadis

PowerAmerica Wide Band Gap Short Course Trains Existing Workforce

SCHEDULE

Day 1 8- 8:30 a.m. Registration
8:30 a.m-5:30 p.m. Class and Laboratory

Day 2 8 a.m.-5 p.m. Class and Laboratory

Day 3 8 a.m.-12 p.m. Class and Laboratory

COURSE OUTLINE

Opening session: Executive Overview

Power GaN Transistor Design Fundamentals and Application

- Where is the state-of-the-art today
- Gate drive requirements and considerations
- Layout techniques for high frequency switching
- Paralleling GaN transistors
- Dead-time requirements
- Thermal management
- High speed measurement techniques
- Design Examples

Practical Implementation of SiC MOSFE for Power Converter De m

- Si IGBT's and SiC MOSFET's si ities and differences overview
- Gate driver de and pcb t
- EMI effects control
- Thermal de and packaging
- Real world de n example of an charger
- ong rm relia and desi argin

Introdu to WBG Module Packaging an pact o Circuit Design

- Electrical desi hallenges for WBG devices
- Pa esses, materials and design requirements
- Advanced packaging technologies
- Full design case study, design creation and hands-on lab experience
- Common failure mechanisms and reliability testing
- System level considerations of WBG power modules

Application of WBG Power Electronics: Power Converters, Electric Vehicles and Motor ves

MV Fast Charger System Specificatio Design Requirements

- Converter topology selection
- Device selection and characterizati
- System modeling and simulations
- Control system specifi ion
- Prototype development testing
- Schematics and PCB design, ware assem and testing
- Control develop and ging
- System timization to m the design requirements
- Demo V SiC fast EV cha r

WBG SiC erter fo ectric and Hybrid Vehicles

- EV Powertrain modeling and simulation
- BG EV traction inverter
- wer stage, gate driver, and controller
- G Circuit Design for high frequency, high perature operation and EMI suppression
- assive Component sizing and selection
- System benefits of WBG insertion

HV SiC Power Device Characterization and Converter Applications

- High voltage SiC device characterization
- Gate Drive isolation, short circuit protection and switching performance
- Power converter design considerations
- High frequency magnetics
- Solid state transformers and MV motor drives

WBG Power Devices and Foundry Tour

- SiC device design and fabrication fundamentals
- WBG devices roadmap, cost model, and projections
- WBG devices characterization: tools and techniques
- High Voltage device testing lab tour
- NCSU foundry tour

SOLD OUT

Industry Driven Short Course Content

2.5 day duration

PowerAmerica Wide Bandgap Conference Tutorials Educate Participants and Promote Mission and Sustainability

2017-2018 PowerAmerica WBG Tutorial presentations at prestigious conferences:

- ✔ "SiC Processing - An Exercise in Si Fabrication with a High Temperature Twist," Veliadis 225 attendees, *International Conference on SiC and Related Materials ICSCRM Sept. 2017*
- ✔ "SiC power device design and fabrication, and insertion in novel MV Power Converters", Veliadis and Bhattacharya, 25 attendees, *IEEE Energy Conversion and Congress & EXPO (ECCE) Oct. 2017*
- ✔ "SiC power device design and fabrication: making the transition from Silicon," Veliadis, 160 attendees *International Symposium on Power Semiconductor Devices and ICs (ISPSD), May 2018*

410 Tutorial Attendees in 2017-2018

PowerAmerica Provides Value Beyond DOE Funding and Will Continue to Accelerate WBG Technology Manufacturing

PowerAmerica

- **Networking**
  - Summer/Winter member meetings
  - Summary presentation of all PA projects at meetings
  - Long networking breaks at meetings
- **Access to Universities and Recruitment**
  - Student presentations, internships
  - Job opportunities posted on website
  - Collaborative research projects
- **Education and Workforce Development**
  - WBG short course offering with industry driven content
  - Tutorials presented at major WBG conferences
- **Timely Access to PowerAmerica Device Bank Engineering samples**
- **WBG Ecosystem Benefits** such as roadmaps, industry perspectives, technical consulting, member initiated projects, and promotion of SiC and GaN power technology

PowerAmerica accelerates WBG commercialization

WBG device fabrication in large-volume Si foundries exploits economies of scale and is key in lowering cost.

Minimizing capital expenditures by exploiting the mature Si-processing capability lowers fabrication costs.

A workforce well trained in WBG power electronics is key in creating the large device demand that will spur volume manufacturing with its cost-lowering benefits.

PowerAmerica funds building-block projects in multiple areas of the WBG supply chain that synergistically culminate in large-scale WBG power electronics adoption.

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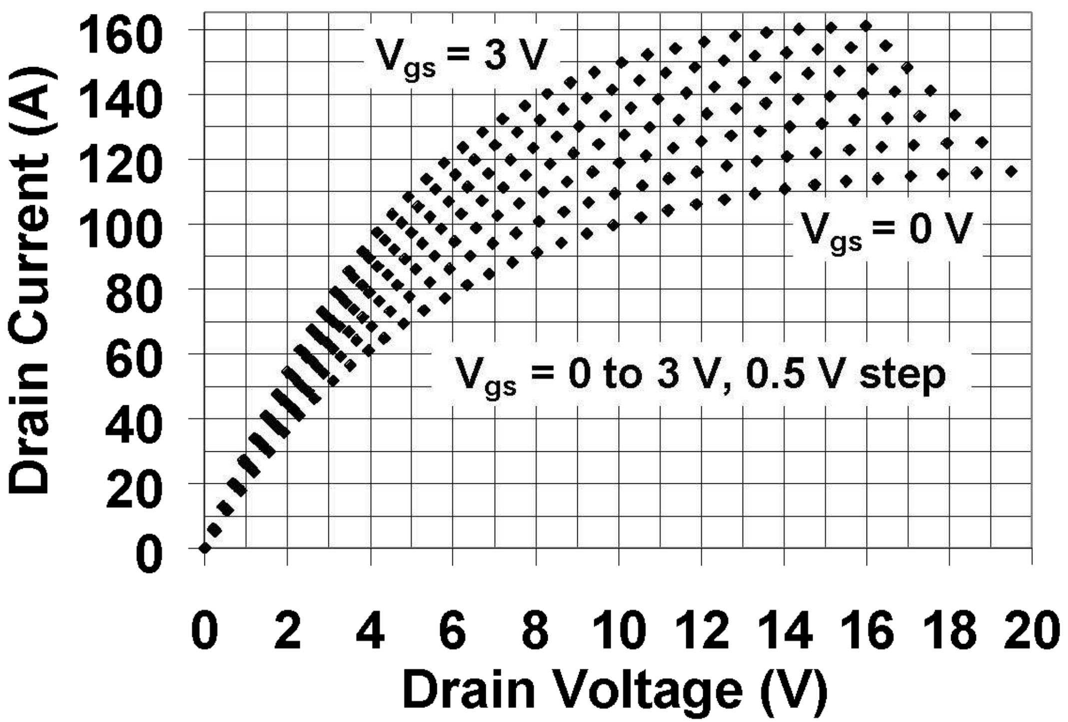
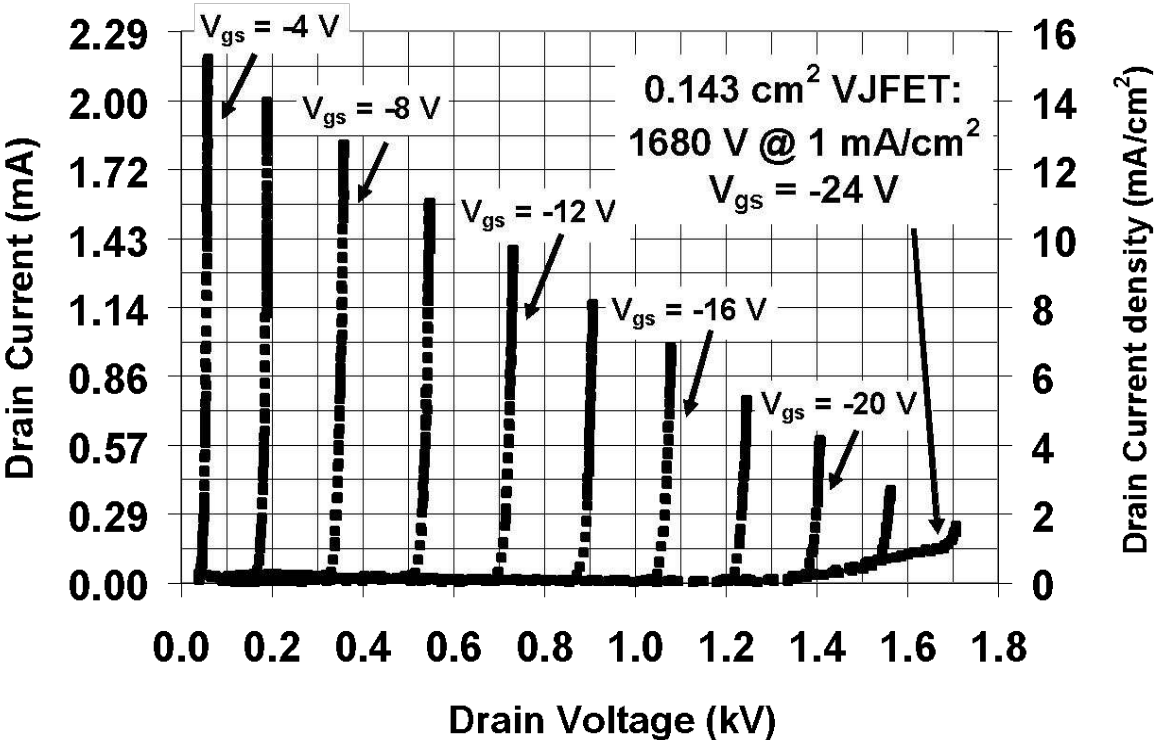
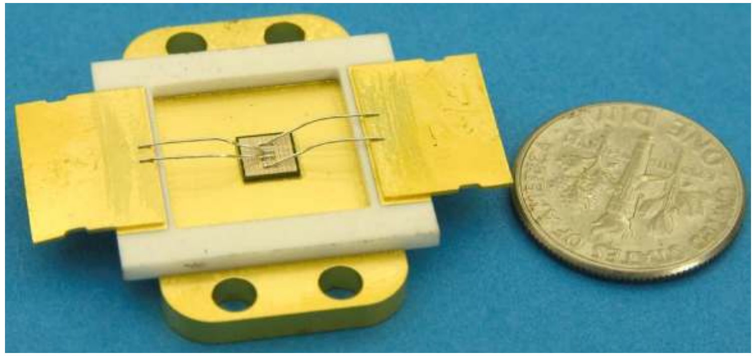
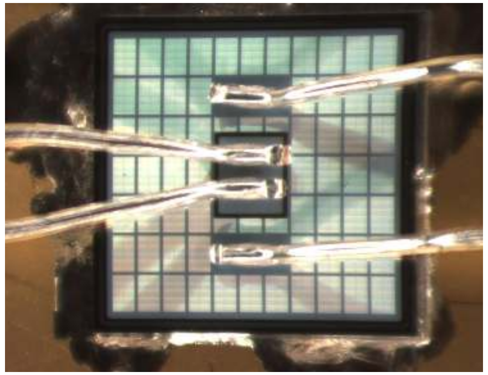
NC STATE UNIVERSITY

0.19 cm^2 Area SiC JFET Blocks 1700 V and Outputs 54 A at a Voltage Drop of 2 V









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Third Party Testing/Reliability Verification: SiC JFET Electrical Characteristics Do Not Degrade after **2.4 million 1200-V Hard-switch Short-circuit Pulses at 150 °C**

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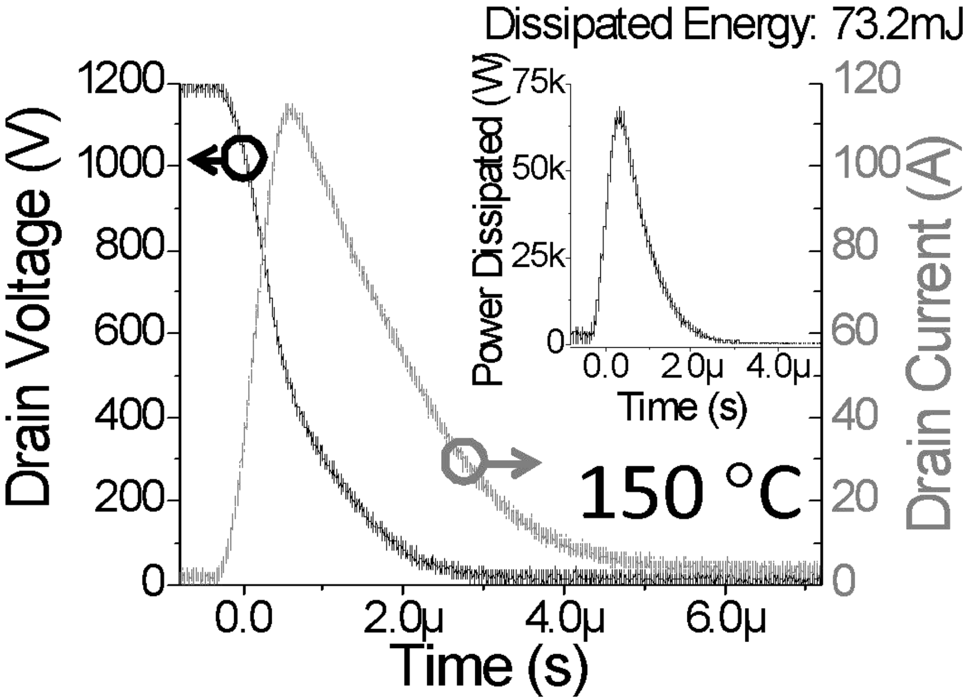
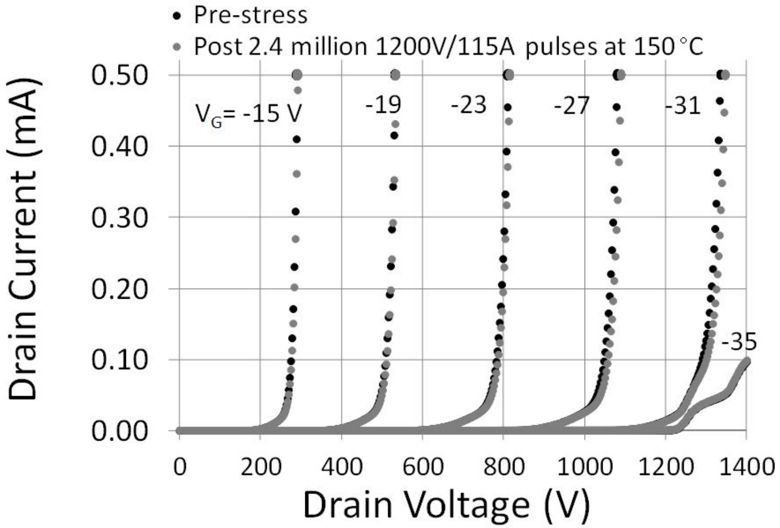
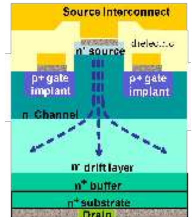




Blocking voltage JFET curves do not change after 2.4 million 1200-V/115-A hard-switch pulses at 150 ºC

- Peak current is 115 A: **13 times the JFET's 250 W/cm² rated current at 150 °C**
- Energy dissipated by the JFET during each hard switching event is 73.2 mJ
- Peak dissipated power: 68.2 kW
- Current rise rate was 166 A/μs and the pulse FWHM was 1.8 μs



TEXAS TECH UNIVERSITY Center *for* Pulsed Power & Power Electronics

ARL

Standardized accelerated testing of large volumes of WBG devices will establish their **Reliability**

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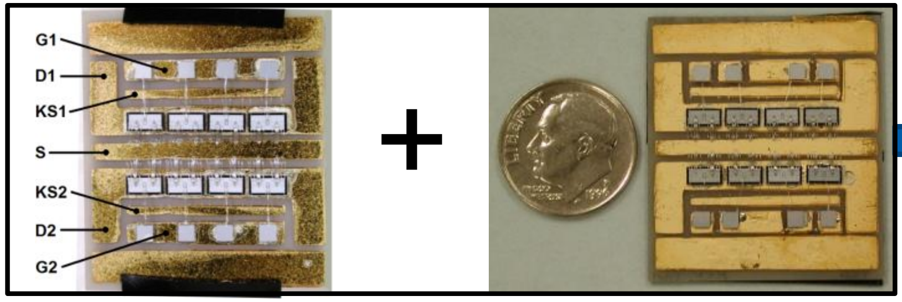
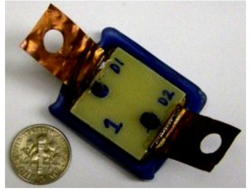
600-V / 60-A SiC JFET Based Bidirectional Power Switching Demonstrated at 25 °C

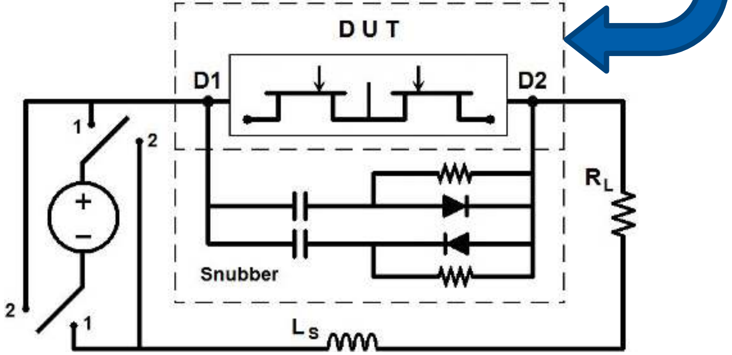
Test conditions:
- 600-V, 60-A (both directions)
- 30˚C liquid cooled heat sink
- Approx 20-µH circuit inductance (12-m cabling)

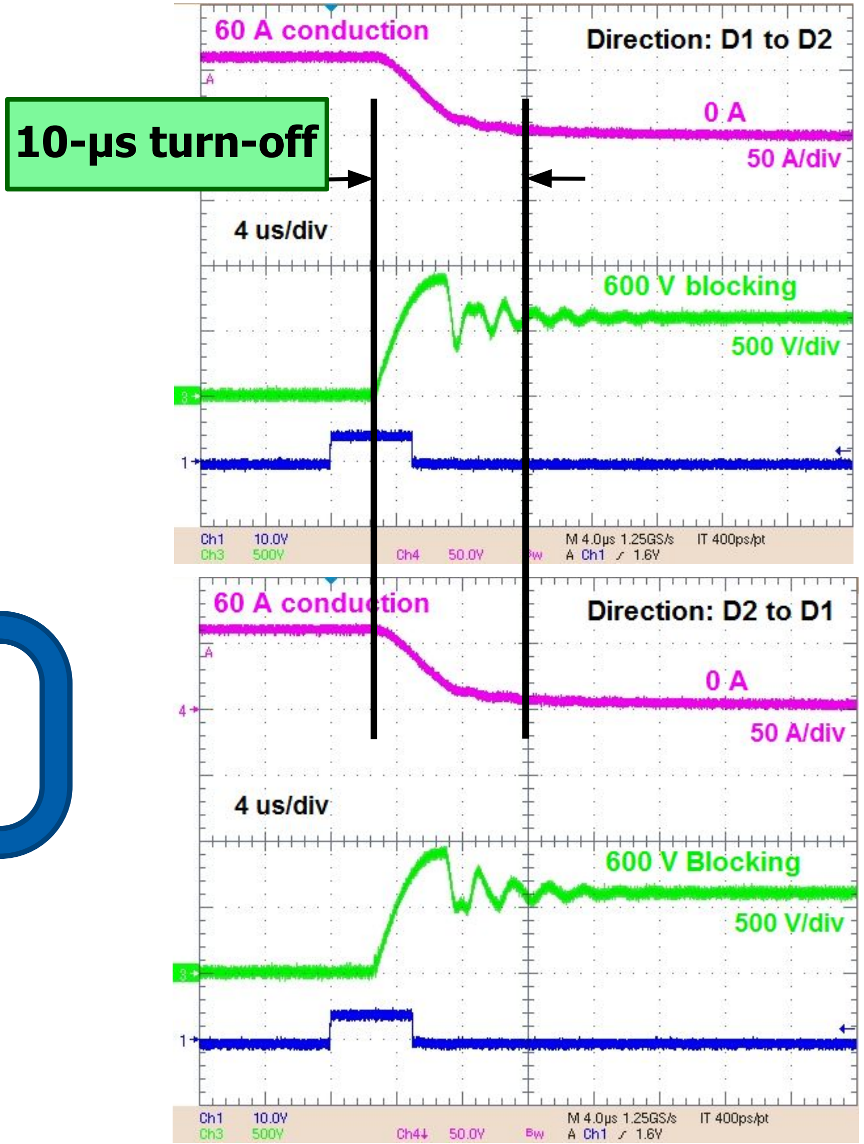
Results:
- 60 to 0-A at 600-V in approx. 10-µs
- Symmetric bidirectional conduction and turn-off
- 300-V overshoot (900-V) peak



Two 30-A modules paralleled for 60-A conduction







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Wafer-scale Interconnection of High-yielding Devices Maximizes Power per Weight/Volume

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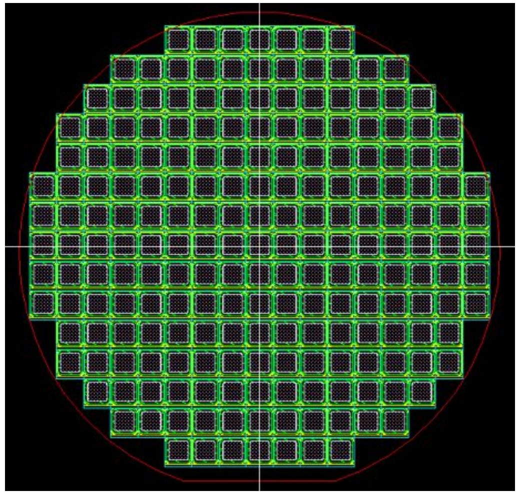
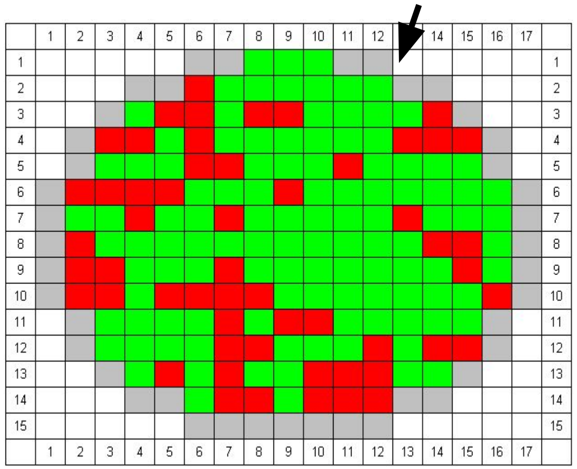
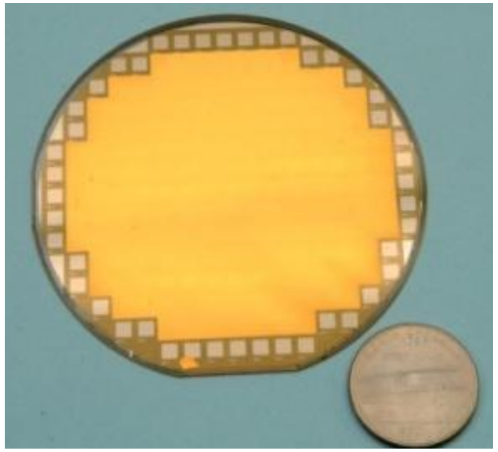
Wafer-scale interconnection approach:

- Determine largest discrete device area fabricated at high yield
- Fabricate discrete devices with edge termination
- Test discrete devices on wafer to generate yield wafer-map
- Interconnect good discrete devices across the wafer (Failed devices are not connected)





GREEN: good, **RED**: failed



Wafer-scale Interconnection

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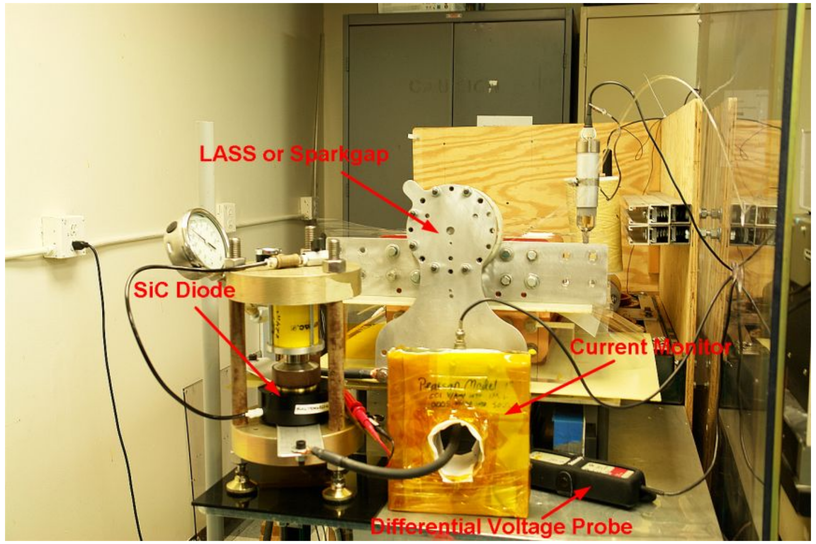
Wafer-scale Interconnected PiN Diode Packaged for Pulsed Testing

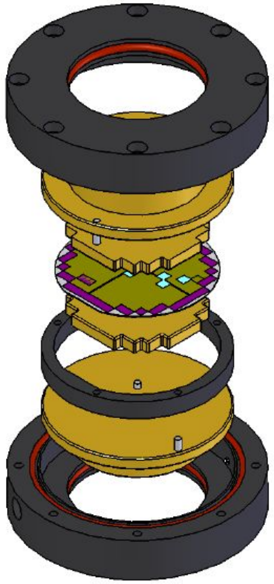
Test-bed developed for wafer-scale diode pulsing:

- 3.1 mF Pulse-Forming-Network (PFN) generates rectangular current pulses
- PFN is switched by a Light Activated Semiconductor Switch or a Spark Gap
- Current Pulse Width: 0.5 ms
- Current Risetime: 33 μs
- Maximum Current: Variable to 96 kA (at 20 kV charge)



Wafer-scale Interconnected PiN diode was press-packaged:

- Press pack accommodates ¼, ½, and wafer-scale devices
- Centering rings are used to ensure even pressure
- Can be pressurized to measure the leakage current in the diode before and after high current shots



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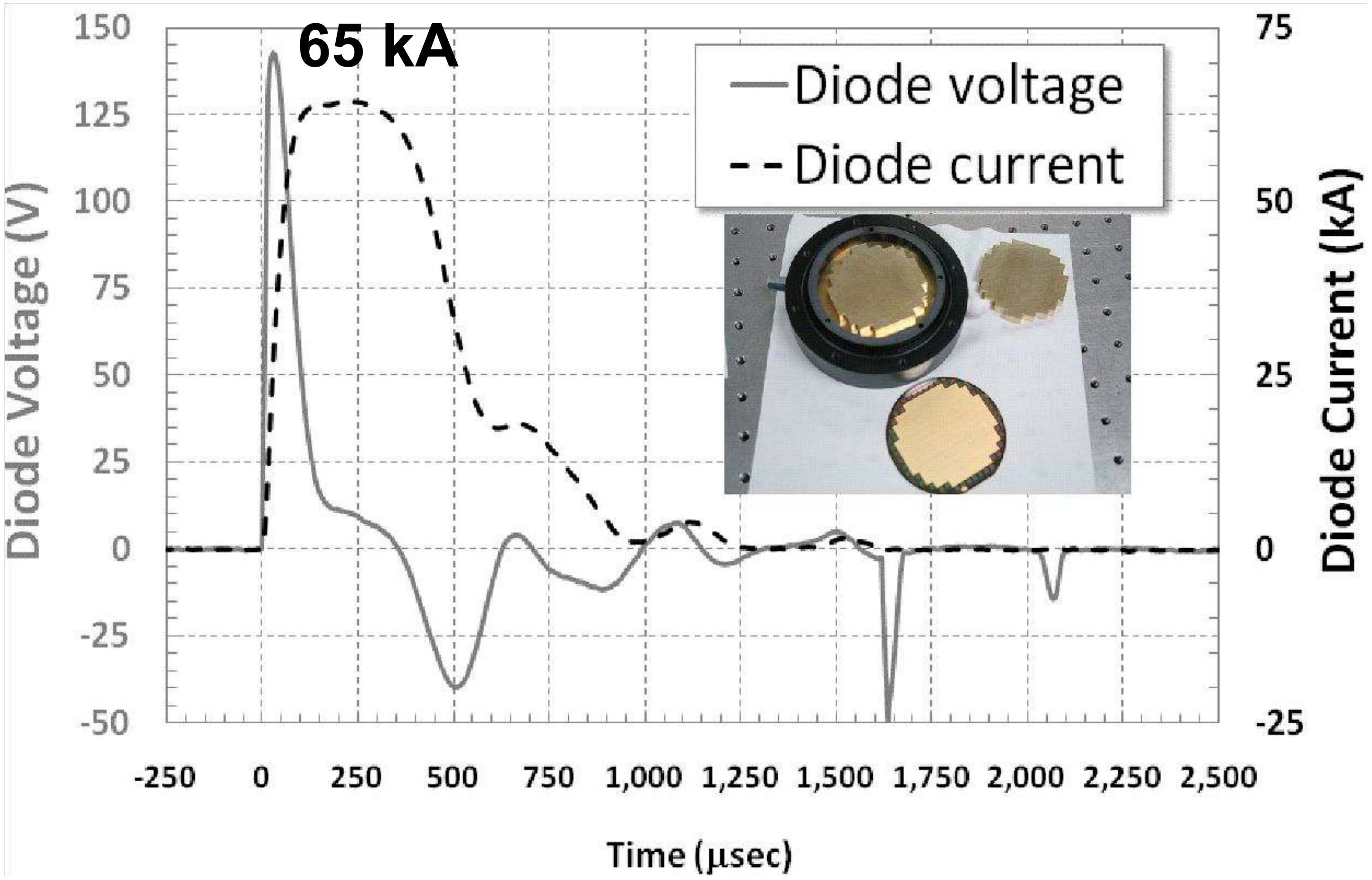
11.7-cm^2 active-area Interconnected 1.8 kV Wafer-scale Diode is Pulsed at 64 kA and Dissipates 382 J



Dissipated Energy = 382 J

R_{diode} = 0.13 mΩ (di/dt = 0)

V_{diode} = 10.3 V (di/dt = 0)

Action = 1.7 MA^2-sec

V_{charge} = 11 kV

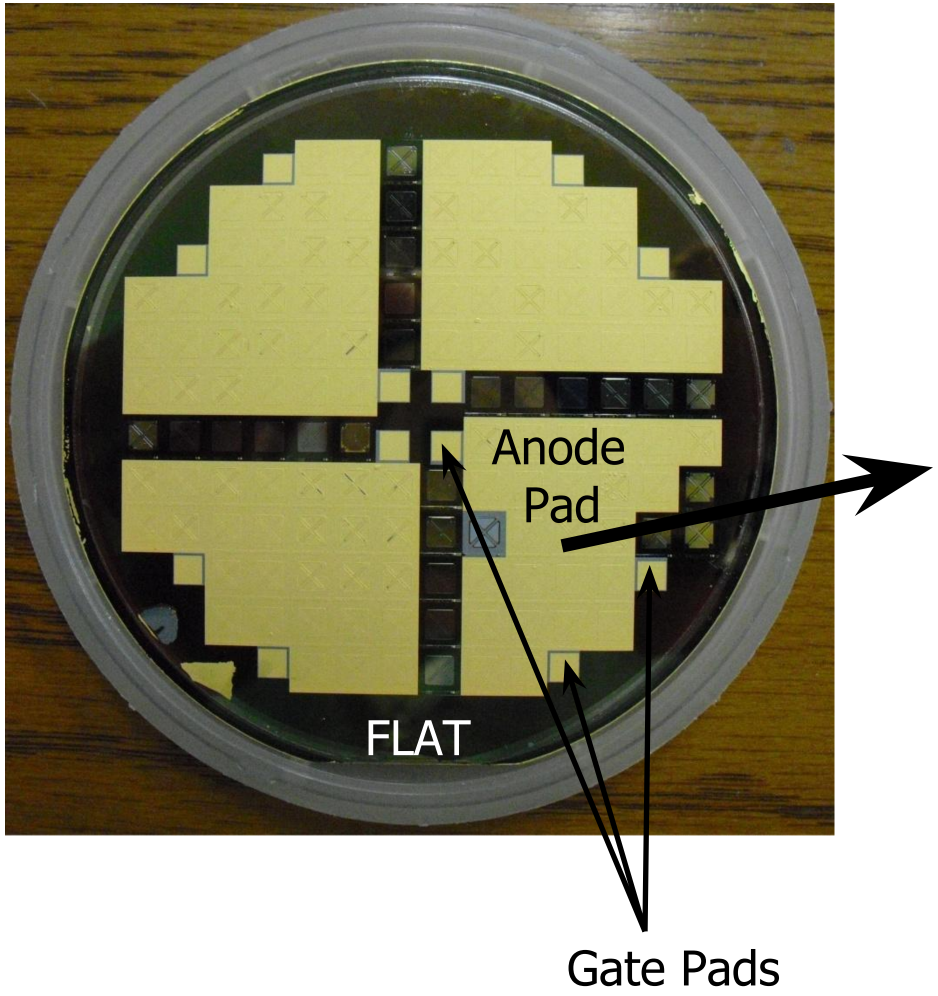
di/dt = 1100 A/µs

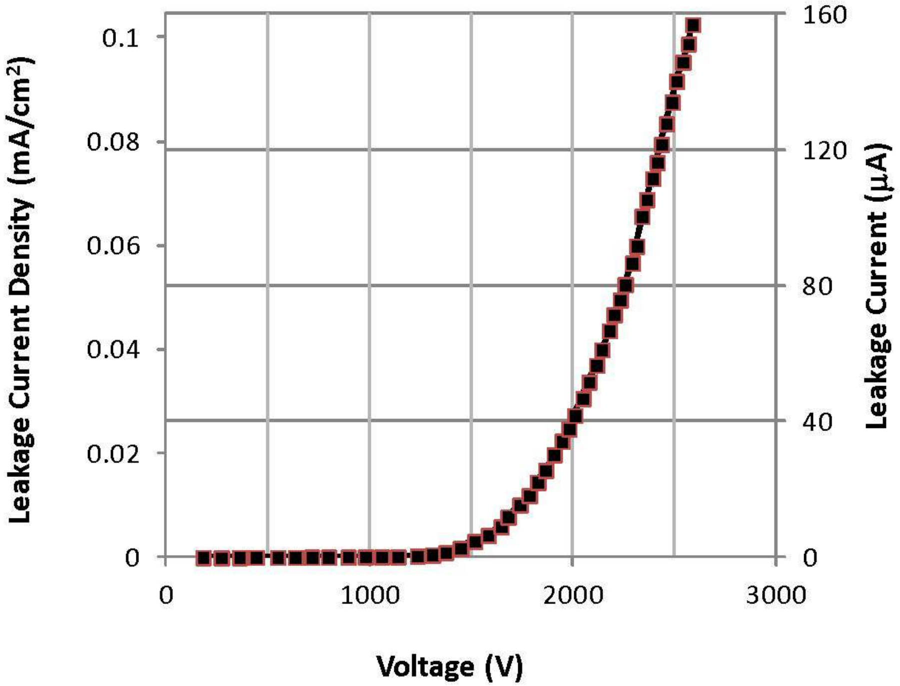
Current Density = 5.5 kA/cm^2

Capacitance = 3.1 mF

Pulse Width = 470 µs

2.6 kV Quarter Wafer Bi-level Interconnected SiC Thyristor Power Switch Demonstrated





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