Power Conditioning Systems for High-Megawatt Fuel Cell Plants

Solid State Energy Conversion Alliance (SECA)

Allen Hefner

NIST

(NIST/DOE Interagency Agreement)

Outline

I. SECA Power Conditioning Systems (PCS)

II. Technology Impact Analysis

III. HV-HF SiC Power Devices

IV. SiC Power Device Cost Reduction

SECA Fuel Cell Plant

Fuel Cell Stack

Power Conditioning System (PCS)

$40-$100 / kW

60 Hz Step-up Transformer

Power Grid

$40-$100 / kW for PCS is a difficult stretch goal !

Power Conditioning System

Objective:

- **High-Megawatt Power Conditioning Systems (PCS) are required to convert:**
  - **from power produced by Fuel Cells (FC) in power plant**
  - **to very high voltage and power required for the grid**

Motivation:

- **DoE SECA cost goals:**
  - **FC generator plant $400/kW**
  - **including $40-100/kW for PCS**
- **Recent Fuel Cell Generator cost *(Fuel Cell Energy Inc.)*:**
  - **FC generator plant $3,000/kW**
  - **including $260/kW for power converter (to 18 kV AC)**
- **Today's SECA cost: $750/kW + PCS cost**

High-Megawatt PCS Program Coordination

- **High-Megawatt Converter Workshop: January 24, 2007**
  - Begin to identify technologies requiring development to meet PCS cost and performance goals for the DOE SECA
- **Industry Roadmap Workshop: April 8, 2008**
  - Initiate roadmap process to offer guidance for further development of high-megawatt converters technology
- **Interagency Advanced Power Group (IAPG): April 21-25**
  - Form interagency task group to coordinate Federal programs in high-megawatt converter technologies - under IAPG ESWG
- **National Science Foundation (NSF): May 15-16, 2008**
  - Establish power electronics curriculums and fundamental research programs for alternate energy power converters

High Megawatt Converter Workshop: http://www.high-megawatt.nist.gov/workshop-1-24-07/

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High Megawatt PCS Technology Impact Analysis

- Perform Independent Analysis of technologies that may reduce cost of PCS for future FC Power Plants
- Methodology for impact study:
  - Include input from broad power electronics, power component, and power engineering communities
  - Classify power converter architectures, topologies, and component technologies that may reduce cost
  - Calculate cost for each PCS option to estimate advantages of new technologies
  - Use component modeling, and circuit and system simulations to verify and refine calculations

300 MW PCS

~700 V DC

Approx. 500 Fuel Cells

~700 V DC

Semiconductors
Packaging and Interconnects
HF transformers
Filter Inductors and Capacitors
Cooling System
60 Hz Transformer up to 18 kV
Breakers and Switchgear

18 kV AC → 345 kV AC

$40-$100 / kW

Ripple < 2%
Stack Voltage Range
~700 to 1000 V

IEEE – 519
IEEE – 1547
Harmonic Distortion
Future: HVDC transmission ?

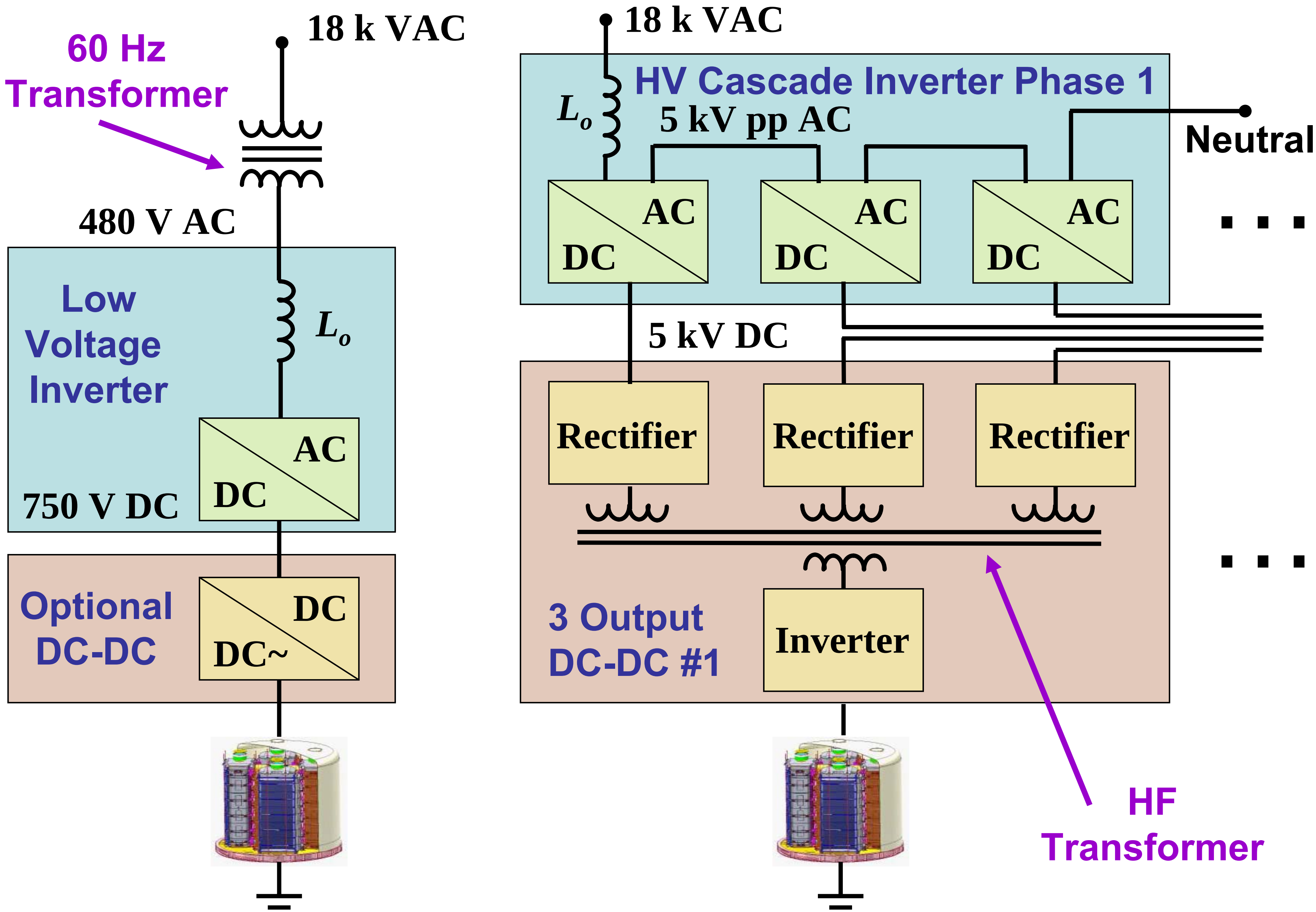
Power Converter Architectures

- <u>**Low-Voltage Inverters (460 V AC):**</u>
  - Require high inverter current for each FC module
  - and large number of Inverters for 300 MW Plant

- <u>**Medium-Voltage Inverters (4160 V AC):**</u>
  - Lower inverter current for each FC module
  - Combine multiple FCs with single high power inverter

- <u>**High-Voltage Inverters (18 kV AC):**</u>
  - Replaces 60 Hz transformer with isolation from HF transformer
  - Cascade enables: 18 kV AC inverter by series connection, and interleaved switching decreases losses and filter requirement

HF Transformer versus 60 Hz Transformer

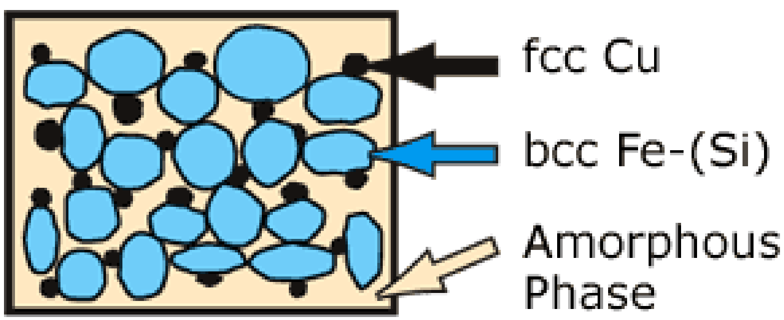


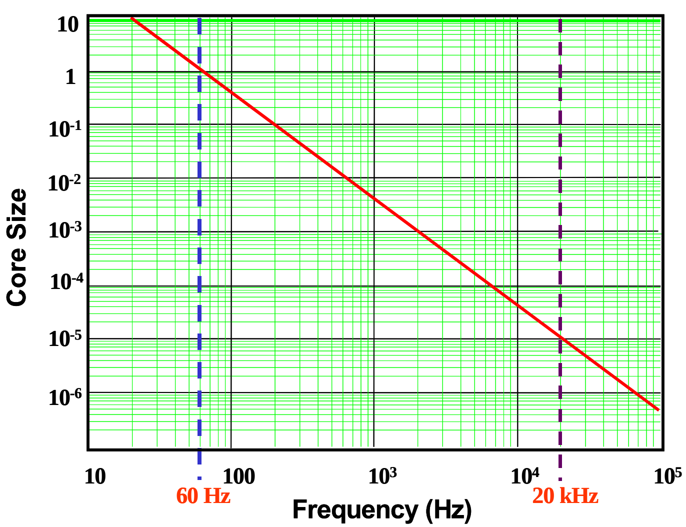
High-Frequency Transformer

- **Baseline: Traditional Ferrite Material**
  - **Expensive processing for high-power, high frequency (HF)**
  - **Mature technology; cost may NOT decrease**

- **HF magnetic materials: Nano-crystalline or Metglas®**
  - **Size and cost decrease inversely proportional to frequency**
  - **Emerging commercial technology; cost continues to decrease**

  - ***What is cost break-point for HF magnetic material?***





High-Voltage Semiconductors

- **Baseline: High-Voltage (HV) Silicon devices (IGBT, IGCT)**
  - **Typically ~6.5 kV blocking voltage maximum**
  - **Requires multi-level inverter for 4160 V AC**
  - **Low switching frequency (< 500 Hz) requires larger filter**

- **High-Voltage, High-Frequency SiC Switch and Diodes**
  - **12 kV, 20 kHz SiC MOSFET switch and SiC Schottky diode:**
  - **Less inverter levels due to higher voltage**
  - **Less loss, lower heat removal cost**
  - **Less filter inductance required due to higher frequency**

  - **15 kV, 5 kHz SiC IGBT switch and SiC PiN diode:**
  - **Higher current per die than SiC MOSFET, therefore lower cost**

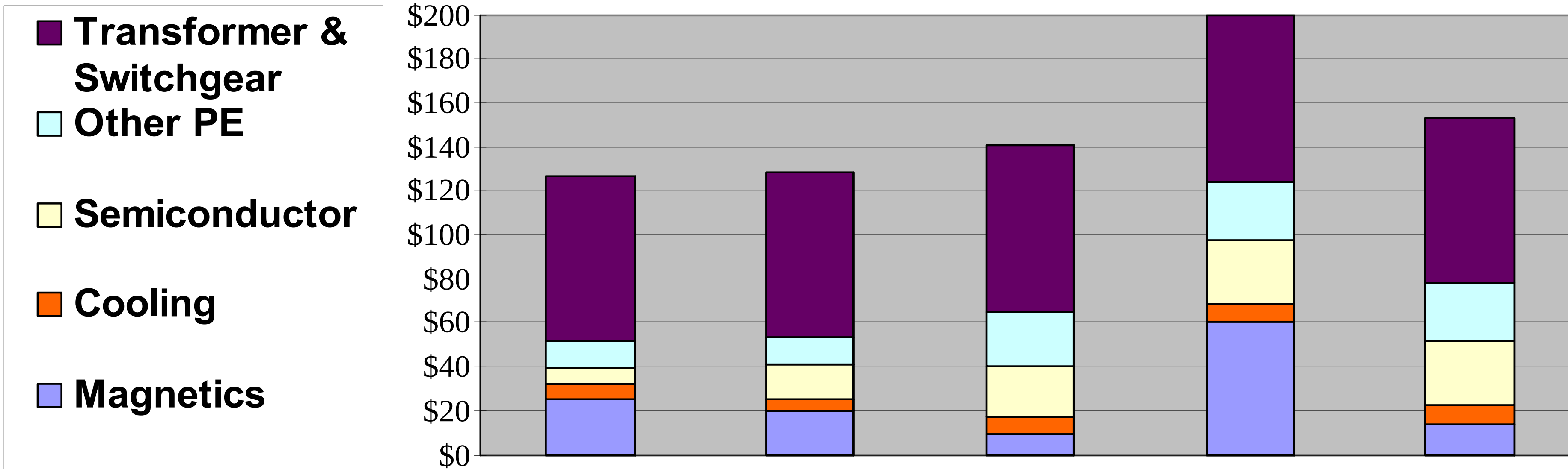
  - ***What is cost break point for HV-HF SiC power semiconductors?***

Advanced Technology Cost

- Future, high-volume costs: 5 to 10 years, 1 GW/yr

- Advanced Technology Goals and Cost Break Points
  - 1.2 kV Schottky diodes: $0.2/A
  - 12 kV Schottky diodes: $1/A
  - 12 kV Half-bridge SiC-MOSFET/SiC-Schottky: $10/A
  - 15 kV SiC-PiN: $0.4/A
  - 15 kV SiC-IGBT/SiC-PiN Module: $3.3/A
  - High-Frequency transformer: $2/kW
  - Power Electronics DC-DC, DC-AC: 150 % overhead
  - 60Hz Transformer and Switchgear: 50 % overhead

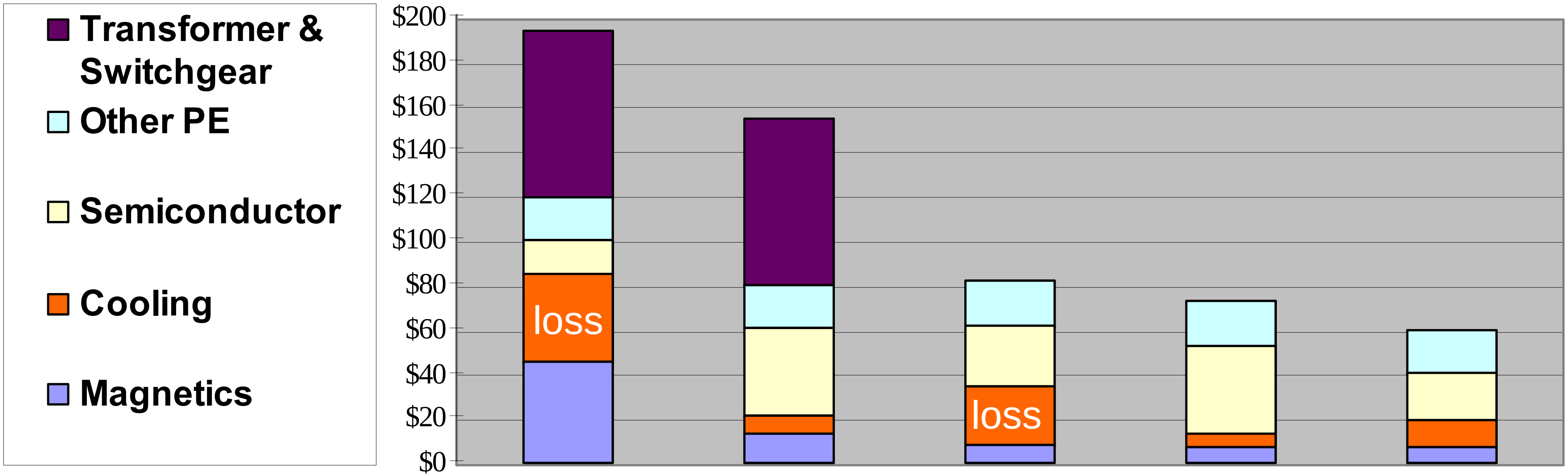
Estimated $/kW: LV Inverter



Inverter Voltage	Low	Low	Low	Low	Low
Converter Stages	One	One	Two	Two	Two
LV-SiC Schottky		yes	yes	yes	yes
HF Transformer				Ferrite	Nano
60 Hz Transformer	yes	yes	yes	yes	yes

Risk Level:	Low	Moderate	Considerable	High

Estimated $/kW: MV & HV Inverter



Inverter Voltage	Medium	Medium	High	High	High
HV-SiC Diode		Schottky	Schottky	Schottky	PiN
HV-SiC Switch		MOSFET		MOSFET	IGBT
HF Transformer	Nano	Nano	Nano	Nano	Nano
60 Hz Transformer	yes	yes			

Risk Level: Low | Moderate | Considerable | High

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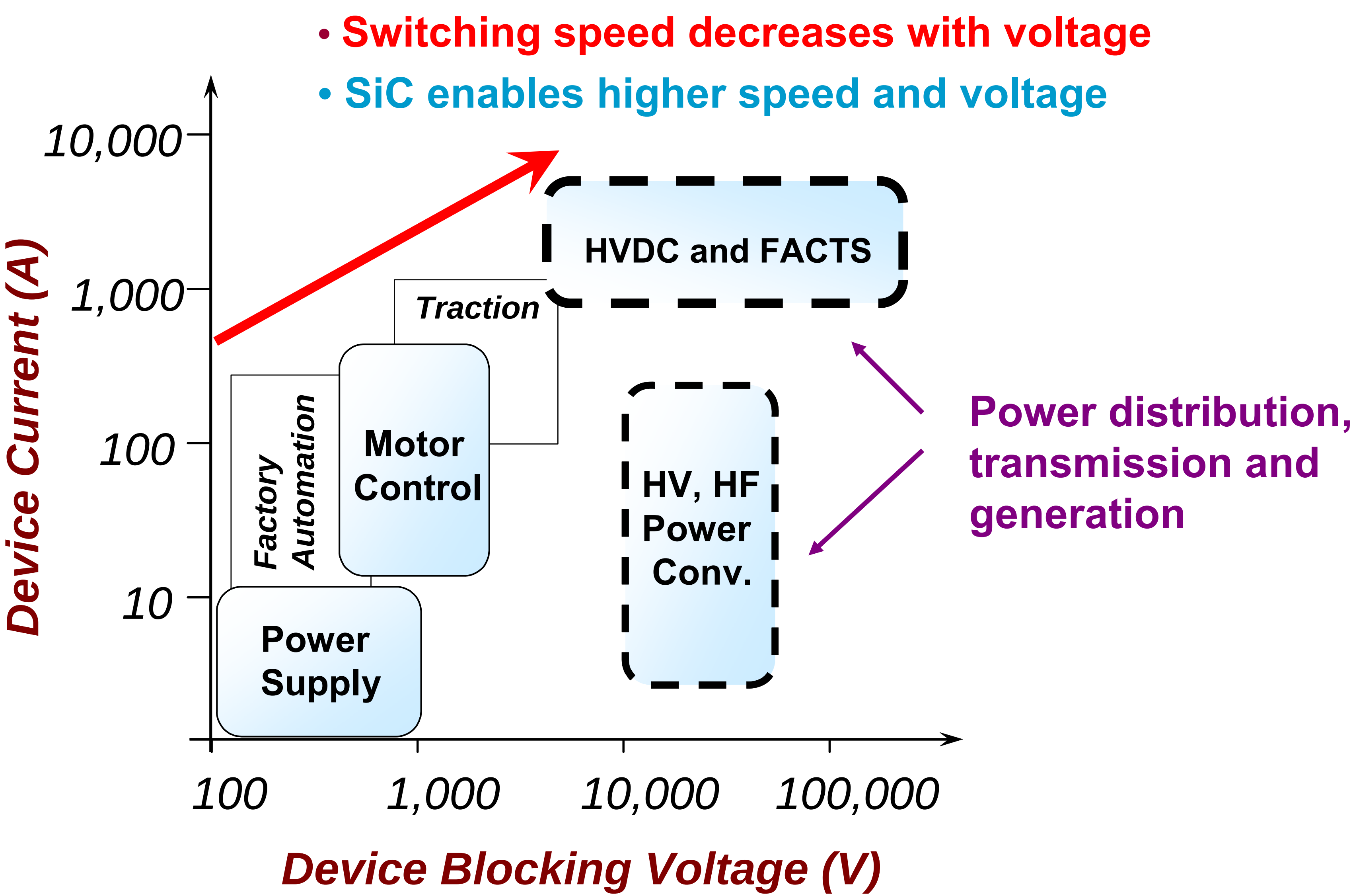
SiC Power Devices

SiC wide bandgap material enables better electrical and thermal performance than Si power devices

Semi-Conductor Material	Energy Bandgap (eV)	Breakdown Electric Field (V/cm)	Thermal Conductivity (W/m·K)	Saturated Electron Drift Velocity (cm/sec)
4H-SiC	**3.26**	**$2.2 \cdot 10^6$**	**380**	**$2.0 \cdot 10^7$**
Si	1.12	**$2.5 \cdot 10^5$**	150	$1.0 \cdot 10^7$

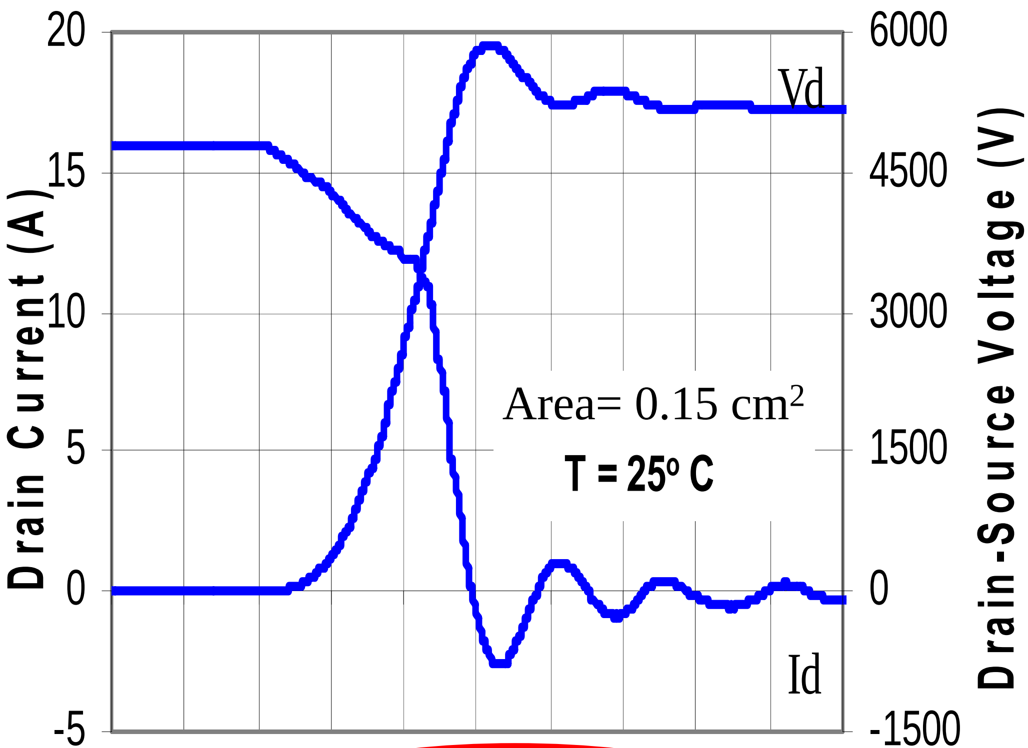
- **Handles higher temperature:** larger bandgap
- **Higher voltage, current and speed:** larger breakdown field
- **Fault tolerance, Pulsed:** intrinsic-temperature, saturation-velocity and thermal-conductivity

Switch-Mode Power Applications



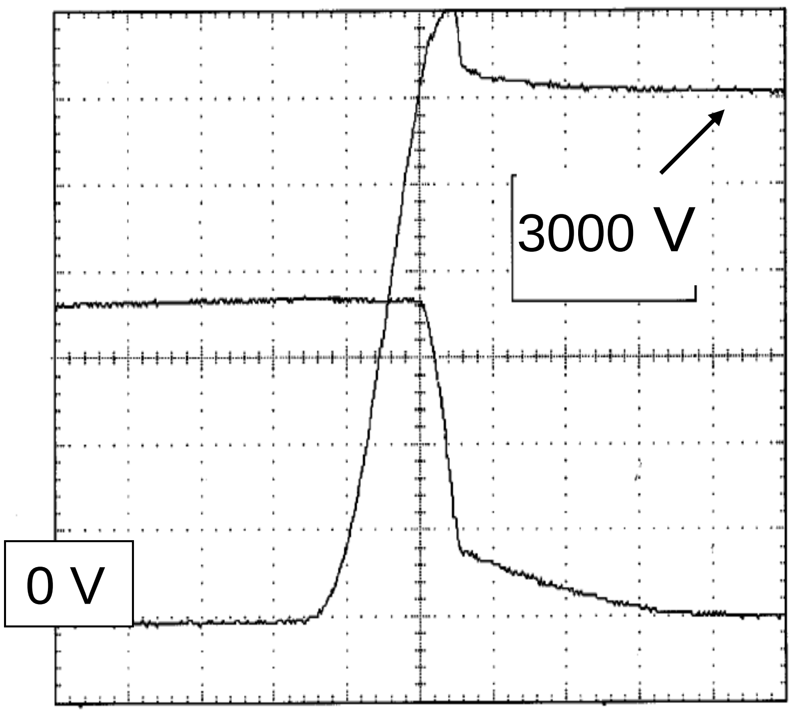
SiC Power MOSFET:
High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns



15 ns /div

Silicon IGBT: 4.5 kV, 2us



1us /div

A. Hefner, et.al. "Recent Advances in High-Voltage, High-Frequency Silicon-Carbide Power Devices," *IEEE IAS Annual Meeting,* October 2006, pp. 330-337.

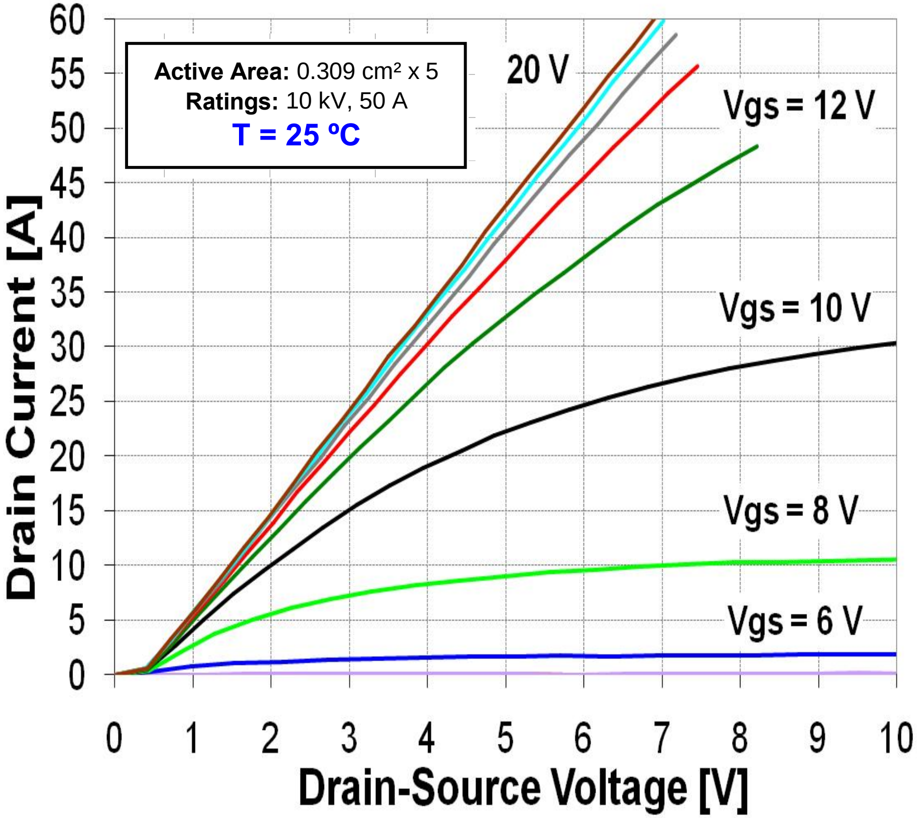
DARPA High Power Electronics Program

- **Phase 2 developed HV-HF SiC power devices:**
- **Phase 3 goal to develop 13.8 kV, 2.7 MVA Solid State Power Substation (SSPS)**

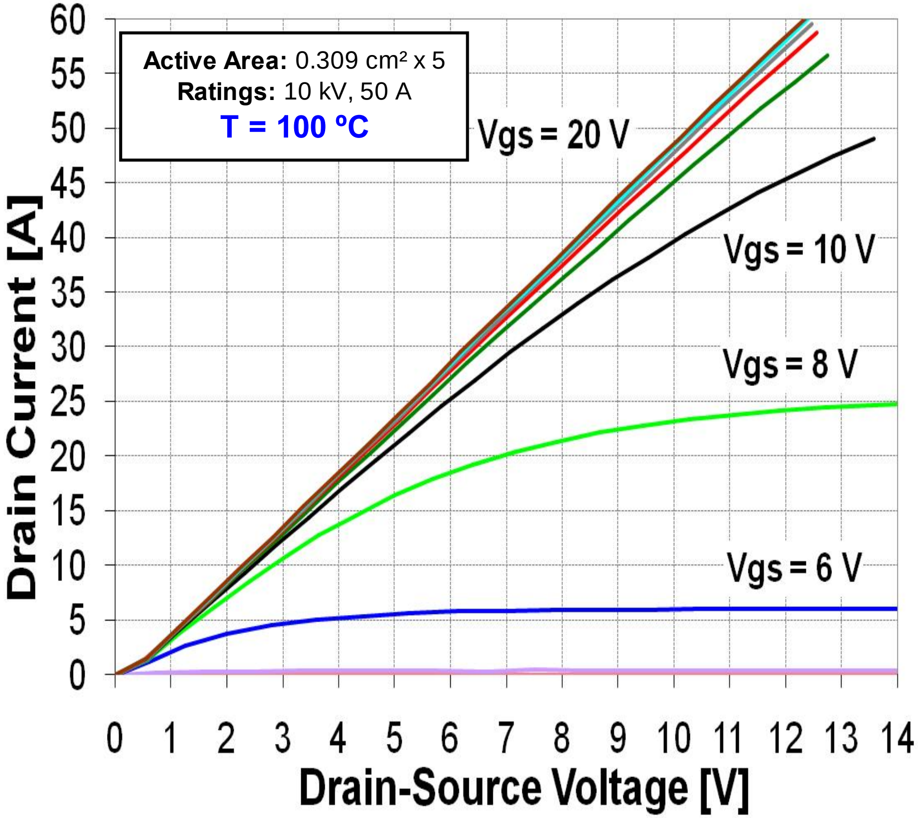
DARPA High Power Electronics Phase 2 Device Development				
	PiN, *(JBS)* (single die)	**MOSFET** (single die)	*IGBT* (single die)*	**Half Bridge Module**
BV (V)	**10 kV**	**10 kV**	*15 kV**	**10 – 15 kV**
Ion (A)	**45 A** *(18 A)*	**18 A**	*25 A*	**110 A**
Tj (°C)	**200 C**	**200 C**	*200 C*	*200 C*
Fsw (Hz)	**20 kHz**	**20 kHz**	*20 kHz*	**20 kHz**

50 A, 10 kV SiC Half-Bridge Module MOSFET Output Characteristics

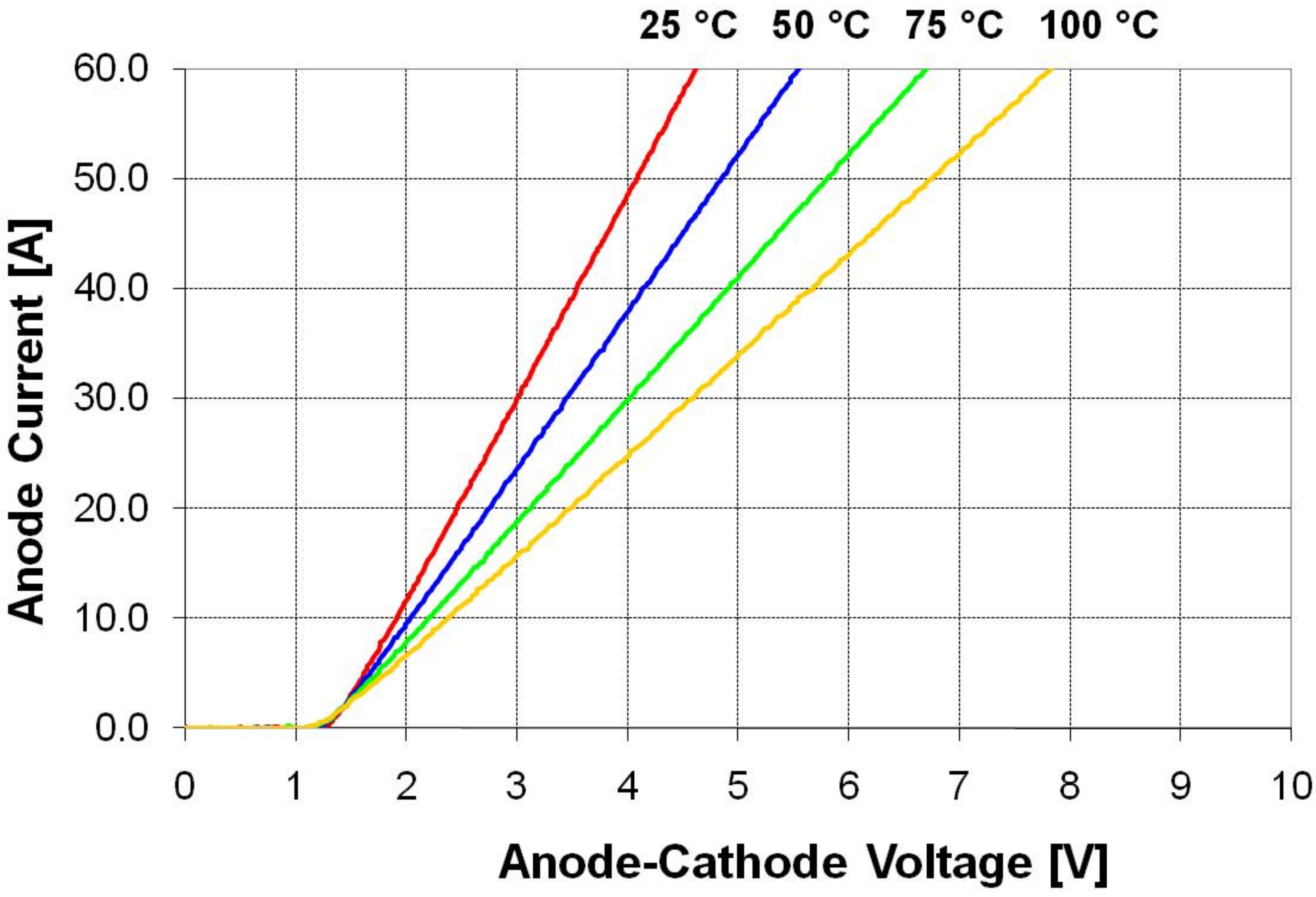
25 °C



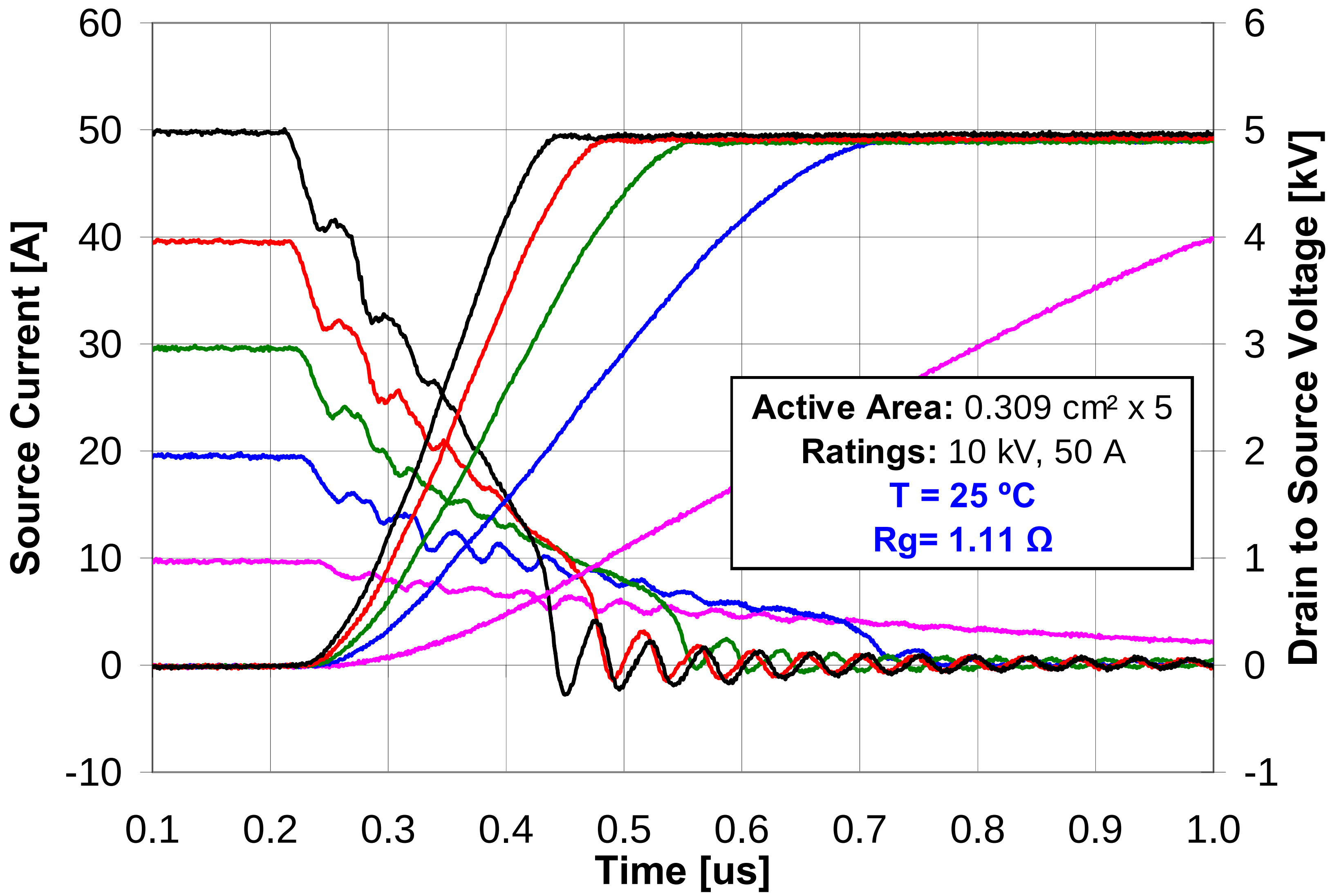
100 °C



50 A, 10 kV SiC Half-Bridge Module JBS Diode Output Characteristics



50 A, 10 kV SiC Half-Bridge Module Inductive Load Switching



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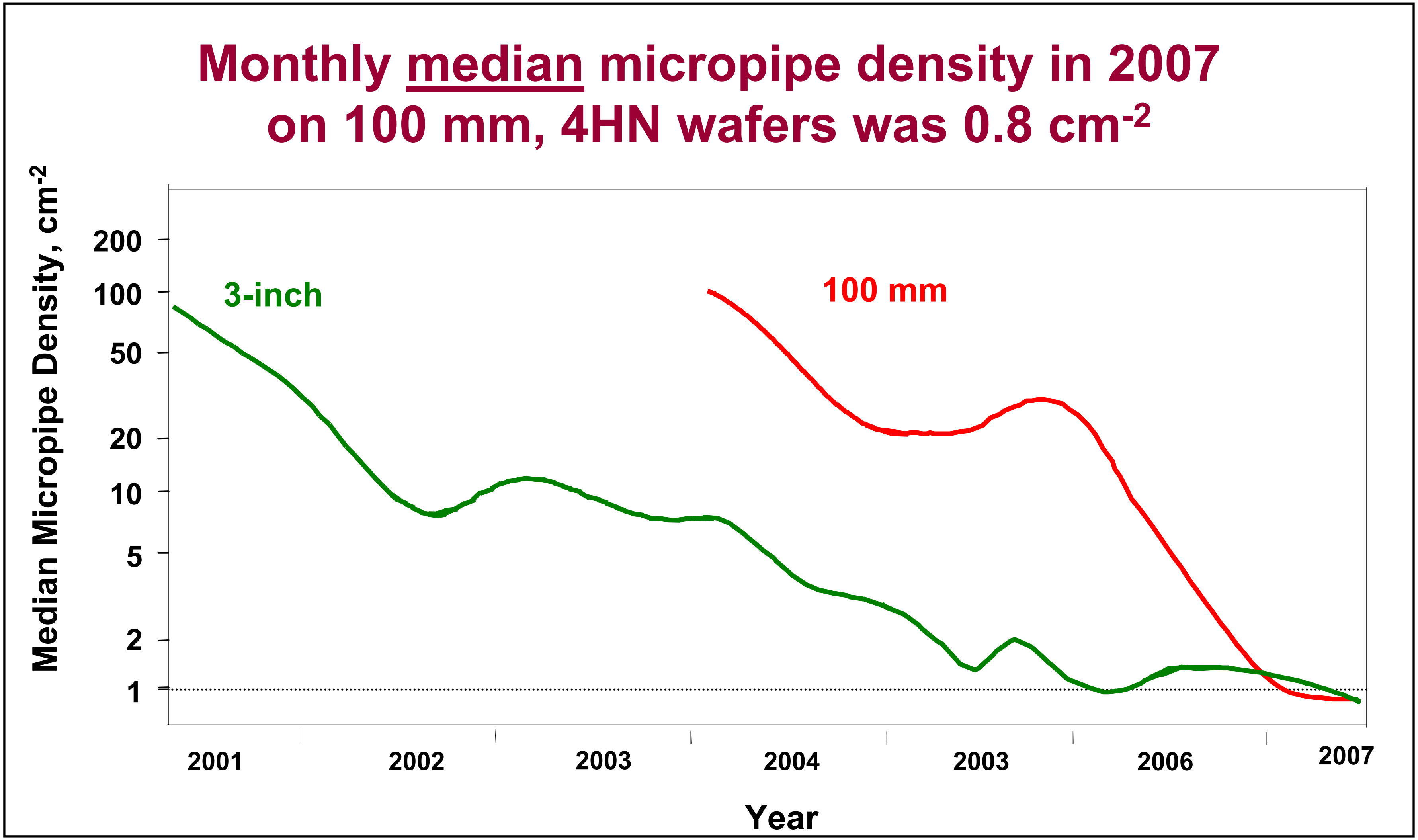
SiC Power Device Cost Reduction

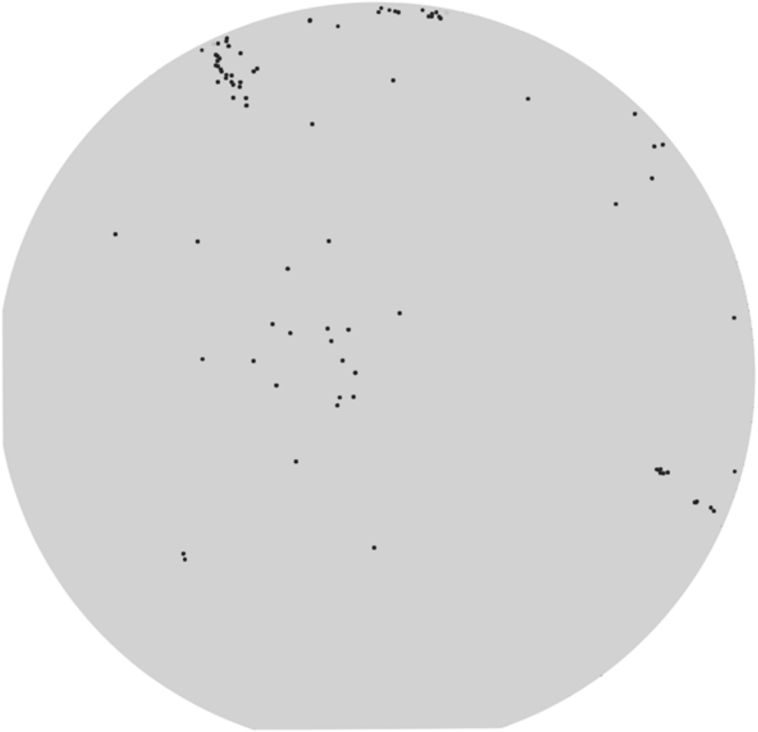
- Improved Crystal Quality required for power devices
  - High conductivity, high field strength type wafers (4HN)
  - Zero Micropipe (ZMP^{TM})
  - Dislocation density reduction
- Wafer diameter expansion required
  - 100 mm is now cost-effective, production platform
  - 150 mm expected in 2009/2010 depending on market needs
- Improved device processing yield for large die area
- Specific needs for different power application type
  - high temperature
  - very high frequency
  - high voltage

Reduction of Micropipe Density



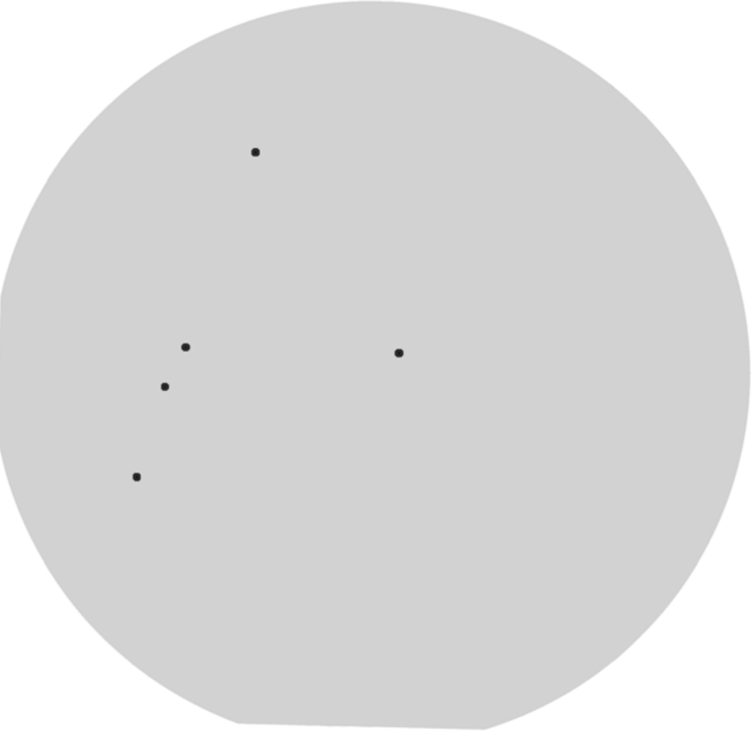
Micropipe Density in 2007 (100 mm 4HN)

Typical



$1\ cm^{-2}$

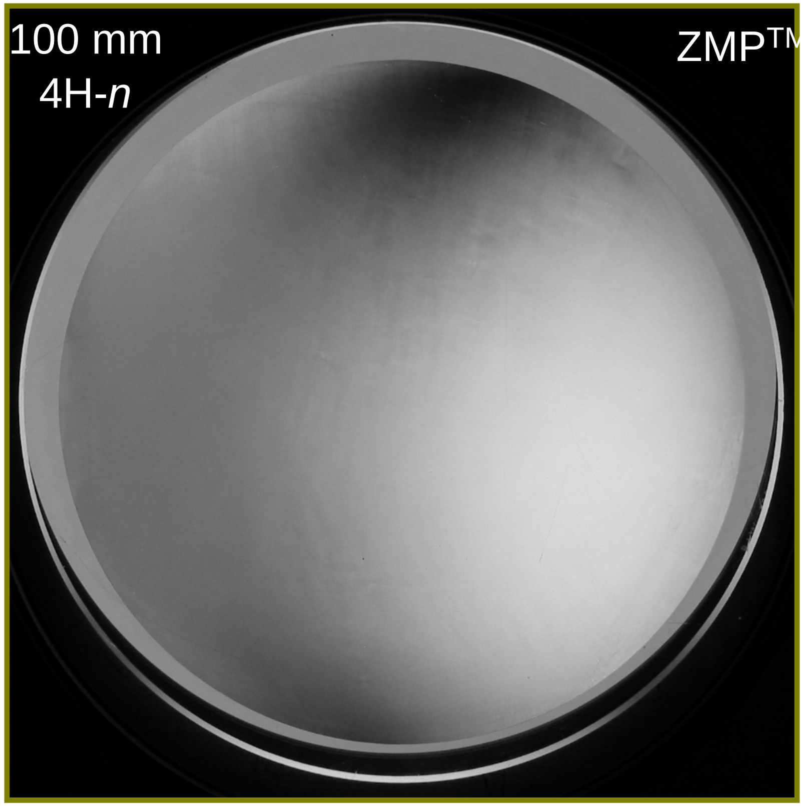
Low

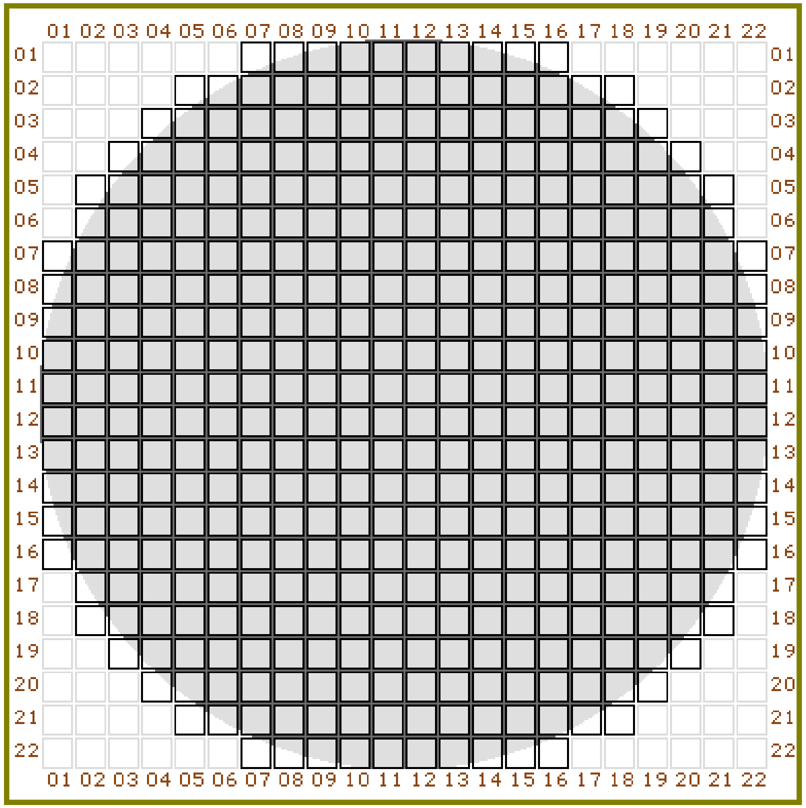


$0.06\ cm^{-2}$

100 mm 4HN Zero Micropipe (ZMP™)

Zero Micropipes with no edge exclusion





Focus on Advancements for High Voltage Devices

- Wafers with reduced 1c screw dislocation density
- Epitaxial structures for >10kV devices
  - reduce ‘killer’ epitaxy defect density to <1 cm^{-2}
  - Improve uniformity of thickness and doping
  - Increase production volumes
- Junction termination, surface passivation and packaging are specific to high voltage devices
- Minority carrier type devices (e.g. IGBTs, PiN diodes)
  - Higher current densities for high blocking voltage devices
  - Requires low basal plane dislocation material

Conclusion

- SECA goal of $40-$100 / kW for Fuel Cell Plant PCS is difficult
- Federal, Industry, and NSF coordination initiated to address High-Megawatt PCS requirements
- Analysis of technologies to reduce cost of PCS
  – high-frequency magnetic materials
  – HV-HF SiC semiconductors
- High voltage inverter enables
  – using low-cost HF transformer
  – instead of costly 60 Hz transformer
- Cost reduction program required for HV-HF devices