SiC High Power Electronics for Naval Platforms

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Outline

- Why Silicon Carbide?
  - SiC vs. S
    - High Voltage (complexity reduction)
    - High Frequency (weight reduction)
- WBG-HPST Program Objectives
    - Materials
    - Devices
- Solid State Power Substation (SSPS) Shipboard Advantages
  - Weight/Volume
  - Design

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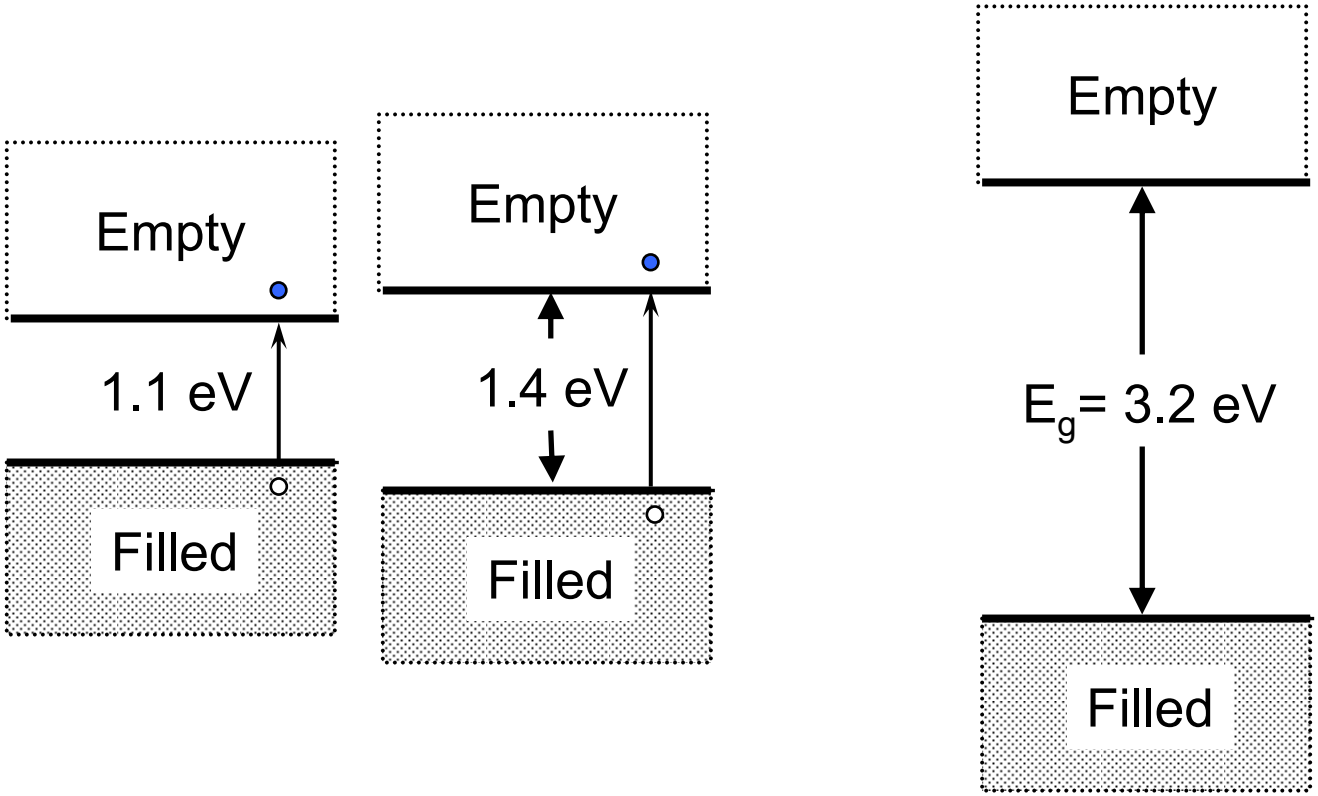
Wide Band Gap Semiconductors
Silicon Carbide

Periodic Table of the Elements

1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	1B	2B	3A	4A	5A	6A	7A	8A
	Covalently Bonded Semiconductors																
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	**La**	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**Ac**															
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Band Diagrams of Common Semiconductors



Silicon **GaAs**

Common Semiconductors

4H-SiC

Wide Bandgap Semiconductor

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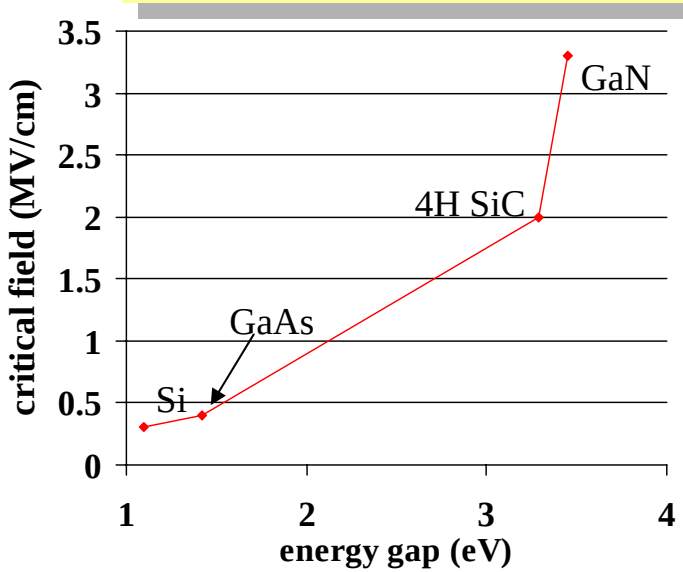
SiC High Voltage Capability

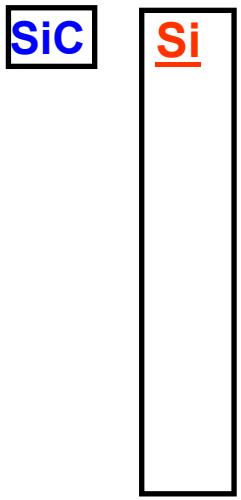
SiC critical electric field
10x Si

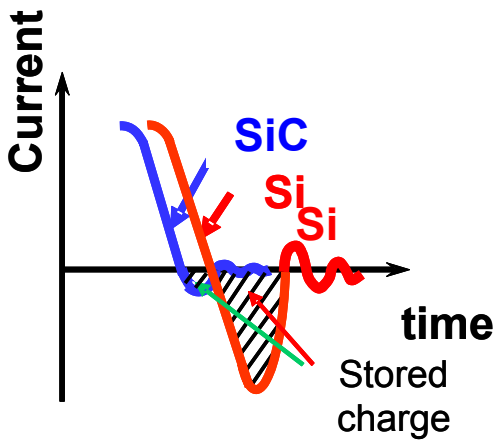


10x reduction in thickness for equivalent performance

Improved Performance
1kV Silicon Devices to 10kV Silicon Carbide Device

High Switching Frequency





Si vs SiC diode switching

- **SiC Power Transistors**
  - **Lower on-resistance**
  - **Lower switching loss**
  - **Higher switching frequency**
  - **High temperature operation**

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Silicon vs. Silicon Carbide 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**	$\mathbf{1.0 \cdot 10^7}$

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

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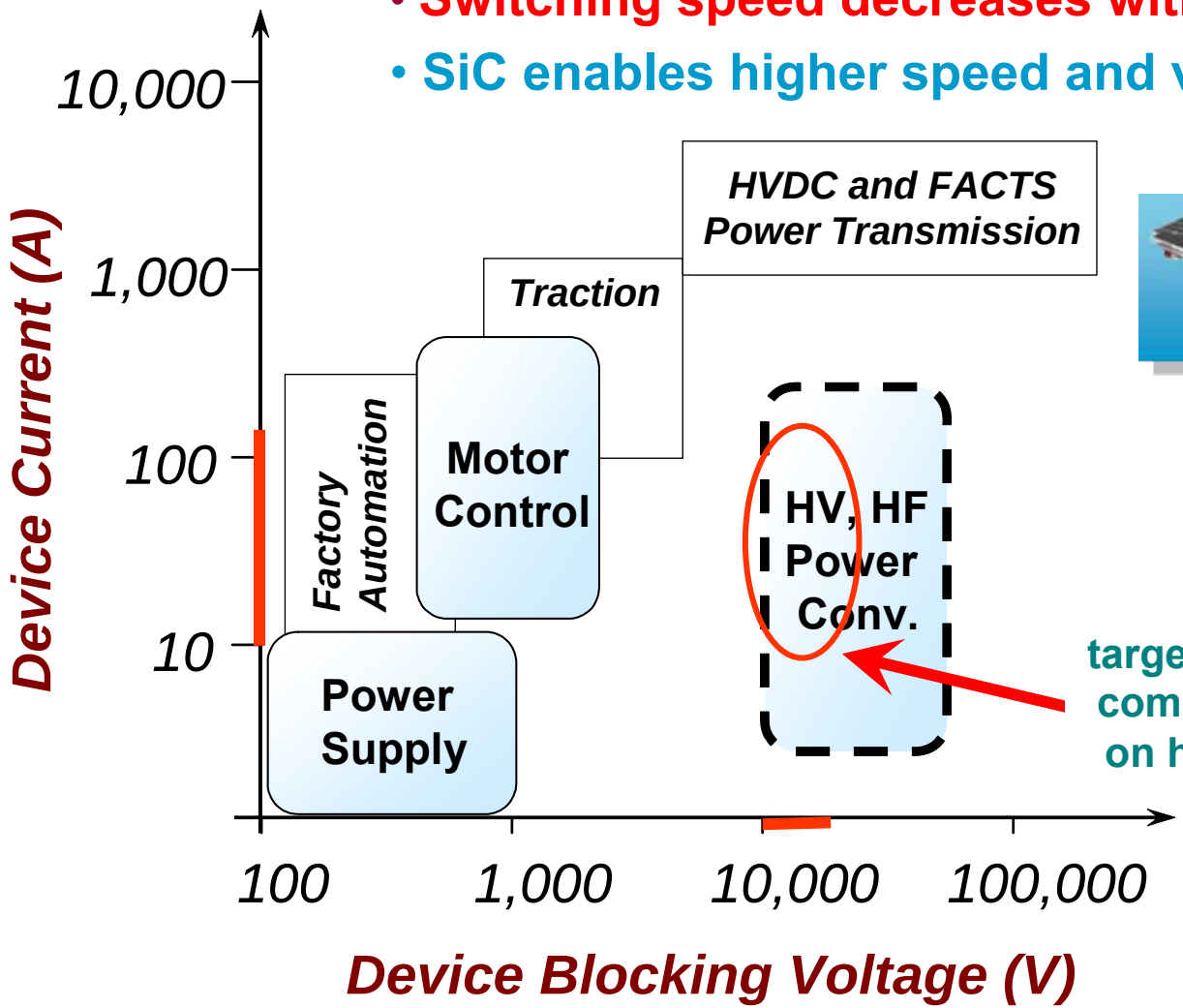
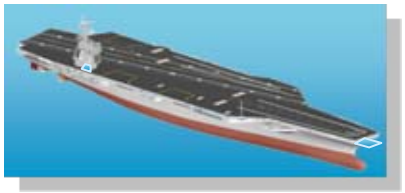
Switching Power Applications

- **Switching speed decreases with voltage**
- **SiC enables higher speed and voltage**





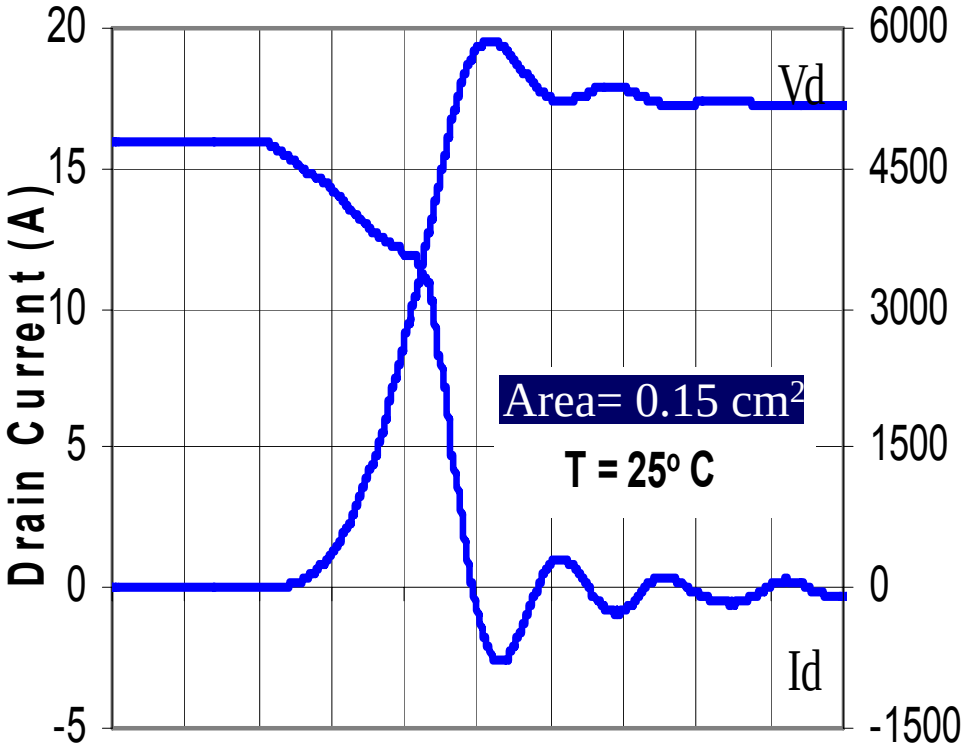
HPE program target: >10kHz, ≥10 kV SiC components for insertion on high power platforms

Benefits of SiC Power Devices

Voltage and Current Range				
BV (kV)	0.3 - 1 kV	2 – 6 kV	10 – 15 kV	20 – 40 kV
Ion (A)	1 - 500 A	50 – 3000 A	3 – 1000 A	200 A
Si Speed	20ns PiN	<1k - 15kHz	---	---
SiC Speed	0ns Schottky	> 20 kHz	50ns, 20 kHz	> 1 kHz
SiC Benefits	Efficiency *High Temp HT Coolant	Efficiency Control	Control Functionality Weight	Control Functionality Part Count
SiC Barrier	Cost *HT Package *MOS mobility/ oxide reliability	Cost Large Area/ Full-wafer-device	Vf degradation HV-HF package *Large area Yield	HV substrate Vf degradation Series Package

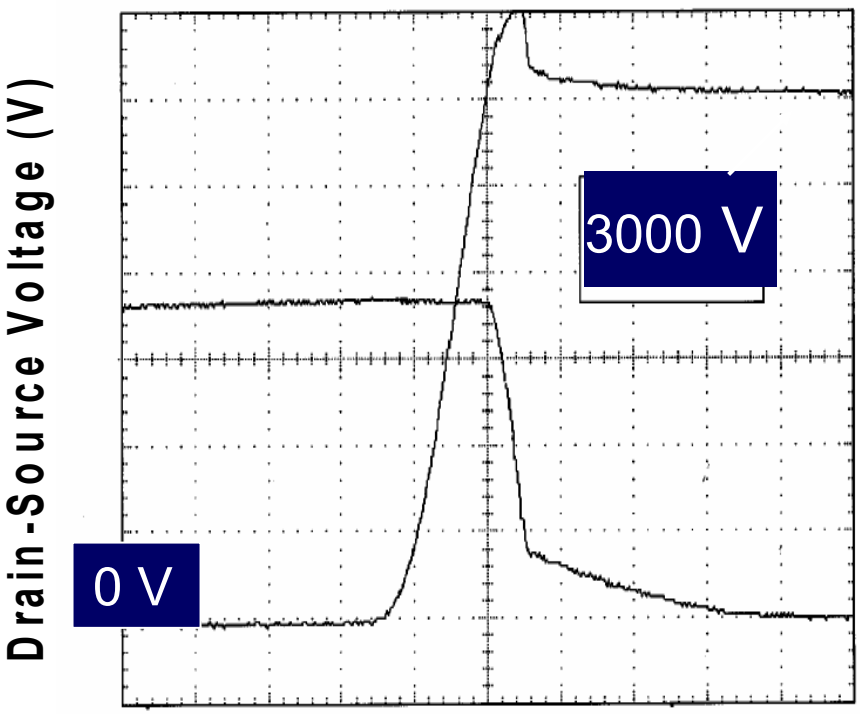
DARPA HPE MOSFET: High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns



15 ns /div

Silicon IGBT: 4.5 kV, 2us



1us /div

Status
Materials, Devices, Modules

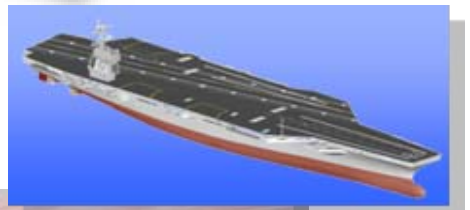
SiC Power Device Applications

Power Transmission

HVAC

Robotics

Servers

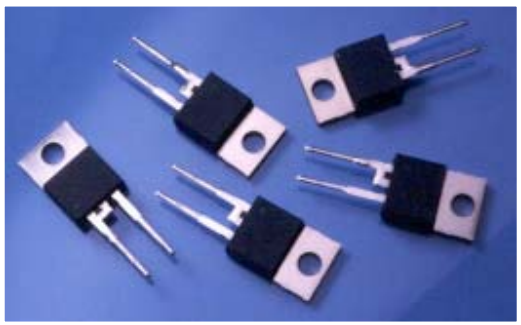


Future Military

Propulsion Drives

Radar Power Supplies

High Power Converters



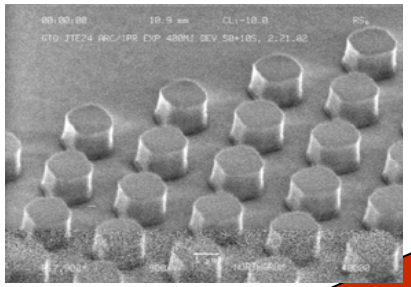
SiC Product Family

Schottky & PIN Diodes

Transistors

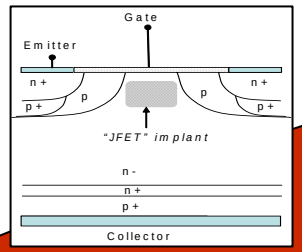
Schottky diodes are commercially available:
300, 600, 1200, 1700 V
1, 4,10, 25 Amps
Hybrid Si MOSFET/SiC Diode Cascode

HPE Objectives & Goals

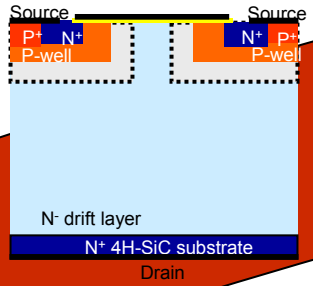


Testing & Reliability

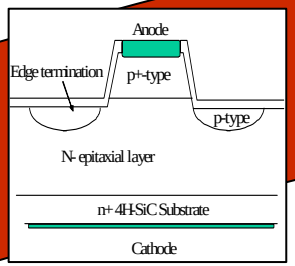
10-20 kV IGBT



10 kV MOSFET



10 kV PiN Diode

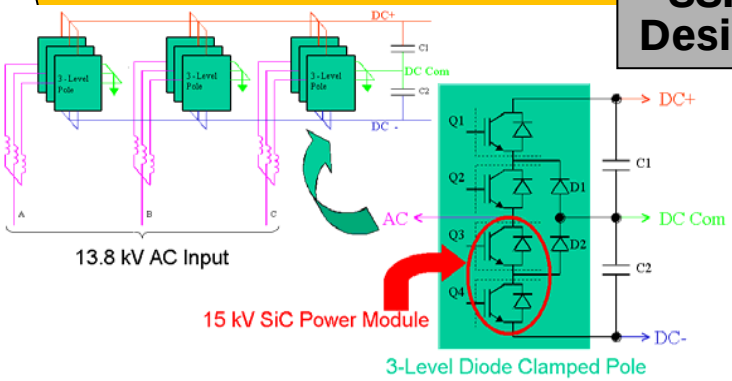


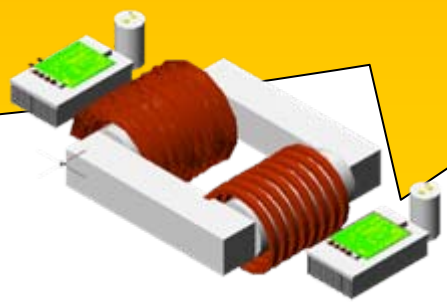
Device Technology

SiC Wafer + Epitaxy

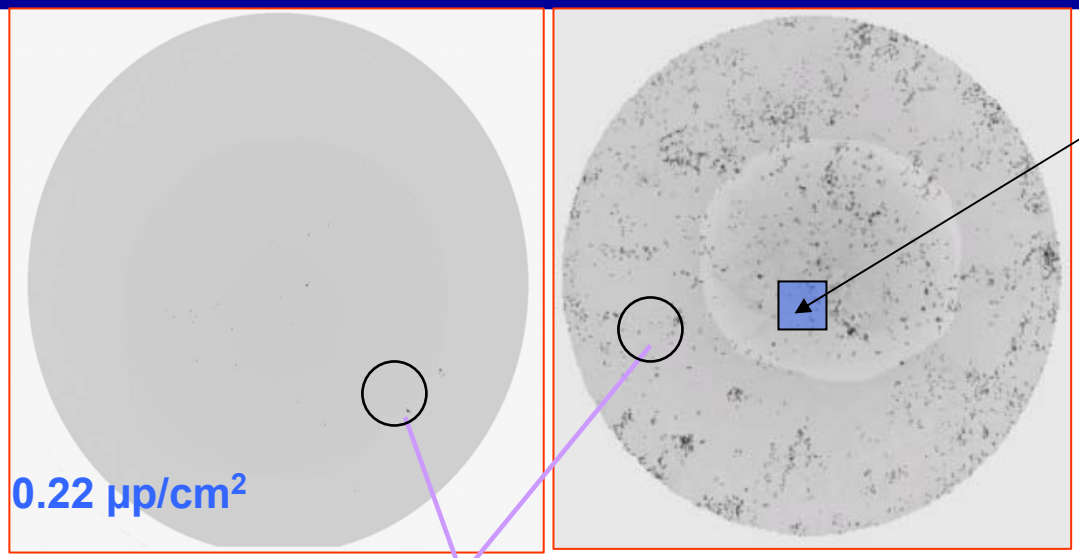
Paralleling & Packaging

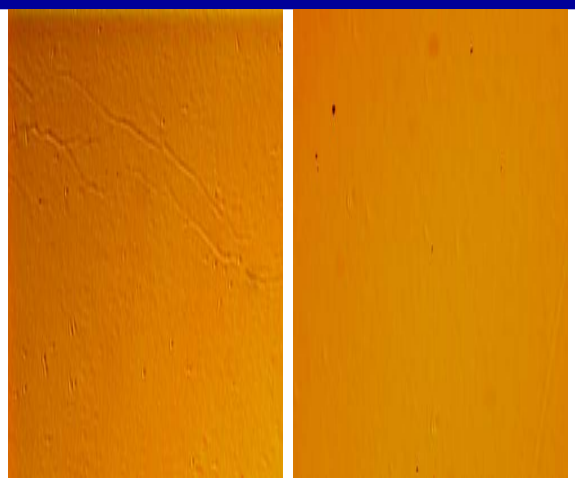
SSPS Designs





Critical Challenge: Material Quality for Large Area Devices

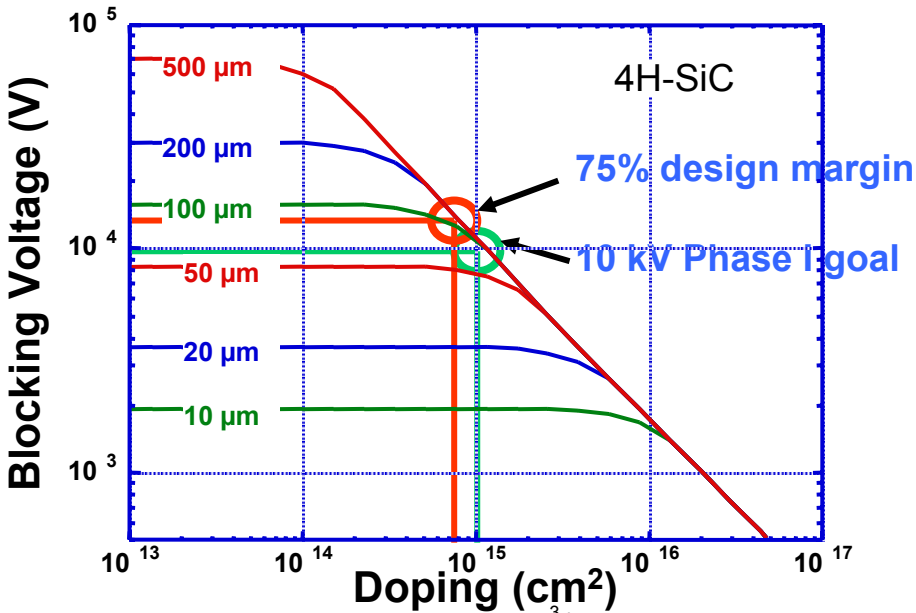




Optical micrographs of 100 µm 4H-SiC epilayer

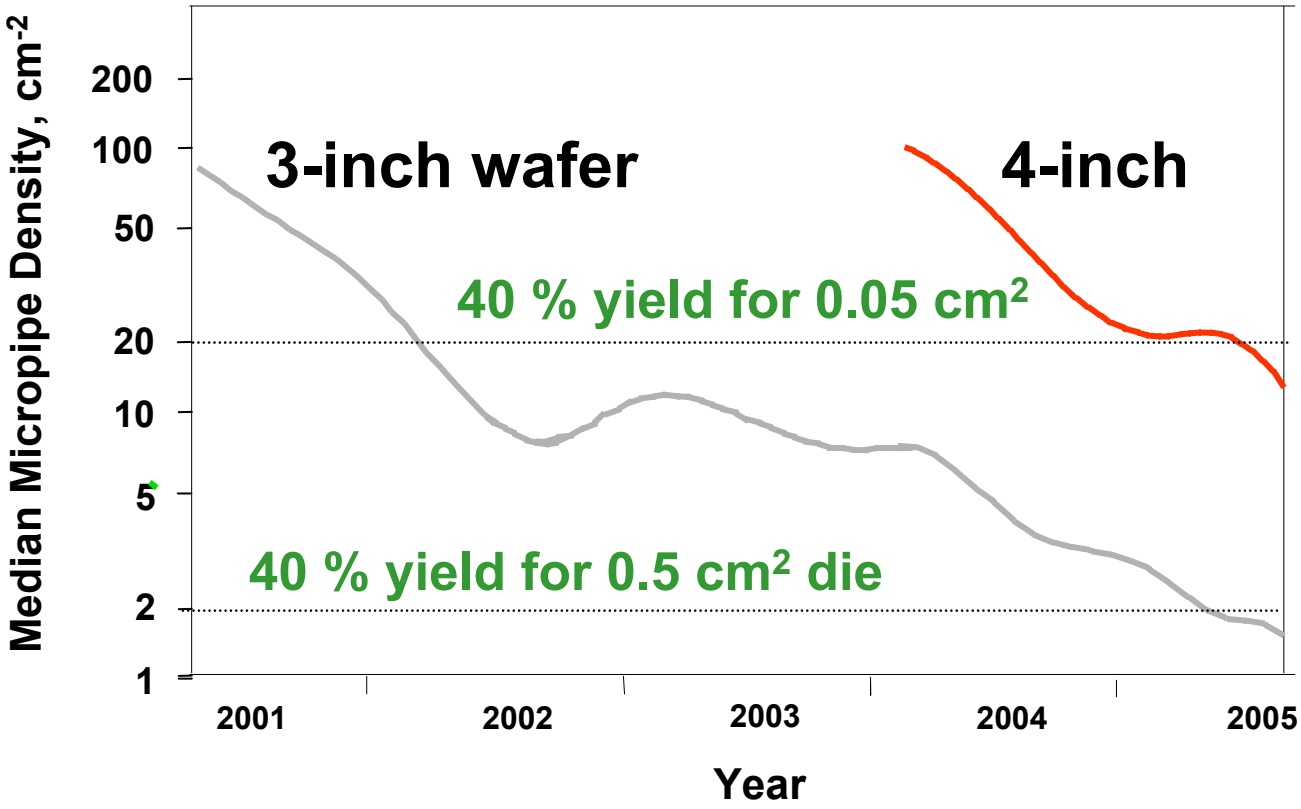
Micropipe: open core dislocation propagating

75 mm 4H SiC n-type wafer



Ongoing Improvement in 4H-N SiC Substrate Quality

- **Monthly Median Micropipe Density (MPD) of 4H n-type SiC Wafers at Cree**
  - **3-inch SiC wafer monthly median Micro Pipe Defects (MPD)< 2 cm^{-2}**
  - **4-inch SiC wafer monthly median Micro Pipe Defects (MPD)< 20 cm^{-2}**



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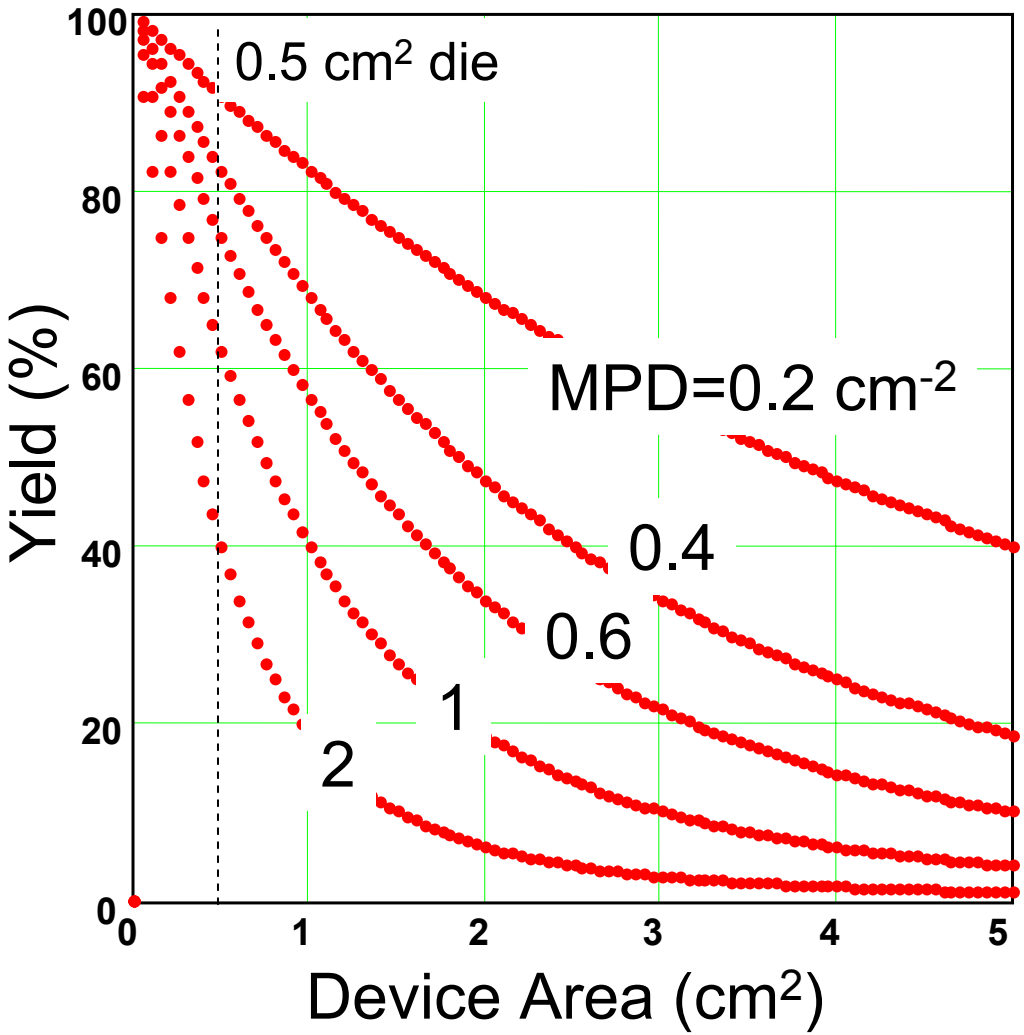
Yield Prediction Based on a Uniform Defect Density



As device area increases, the MPD must be reduced to achieve acceptable yields

For a 0.5 cm^2 die (30 A, 10 kV PIN)

MPD	Yield
10	4%
5	15%
1	60%
0.5	80%
0.2	90%

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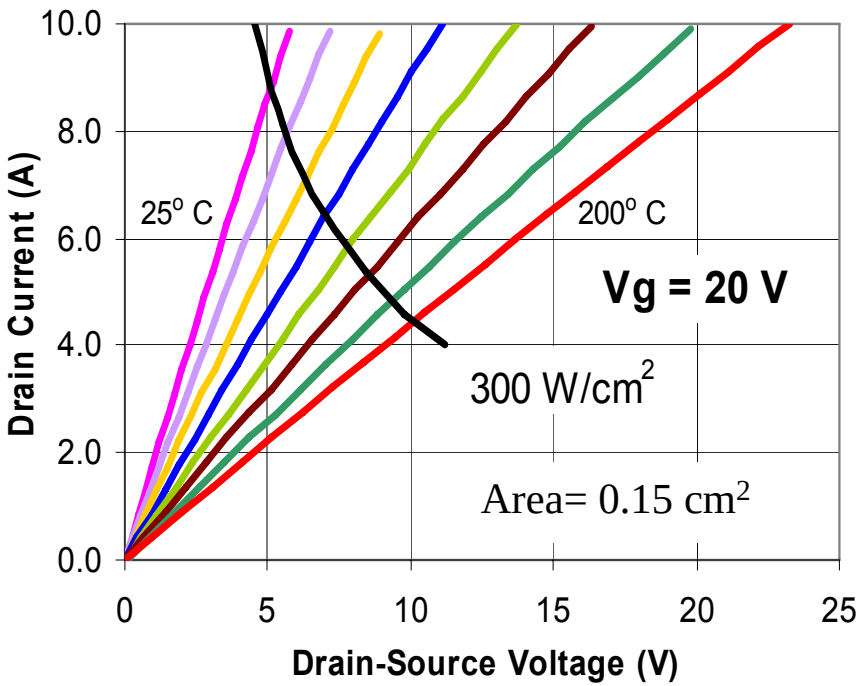
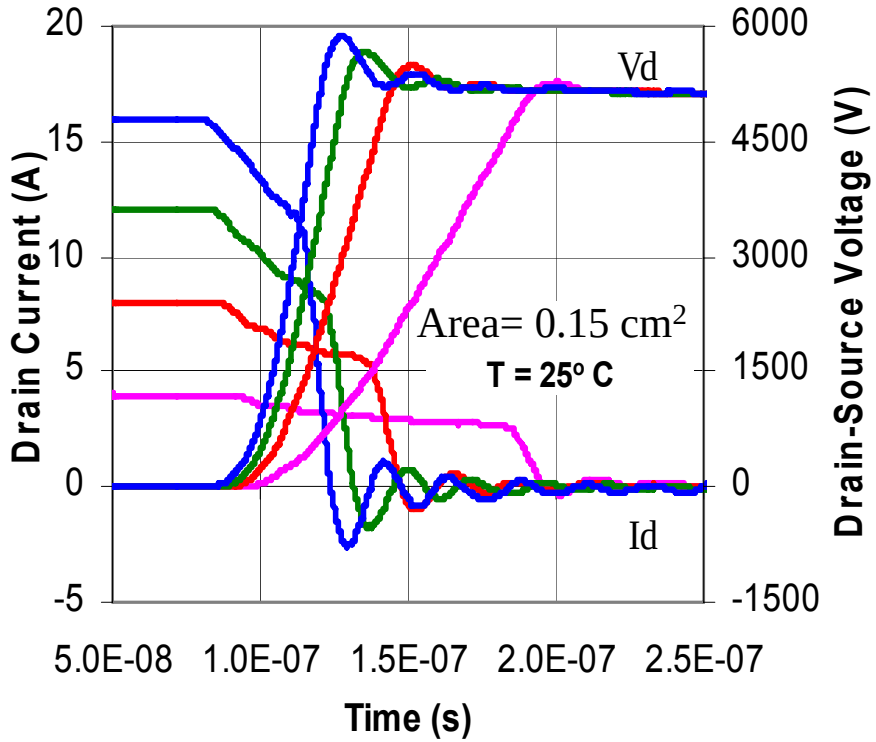
MOSFET

Continuous Current:
30 A/cm² @ 200 C



Extremely Fast Switching:
30 ns @ 120 A/cm²



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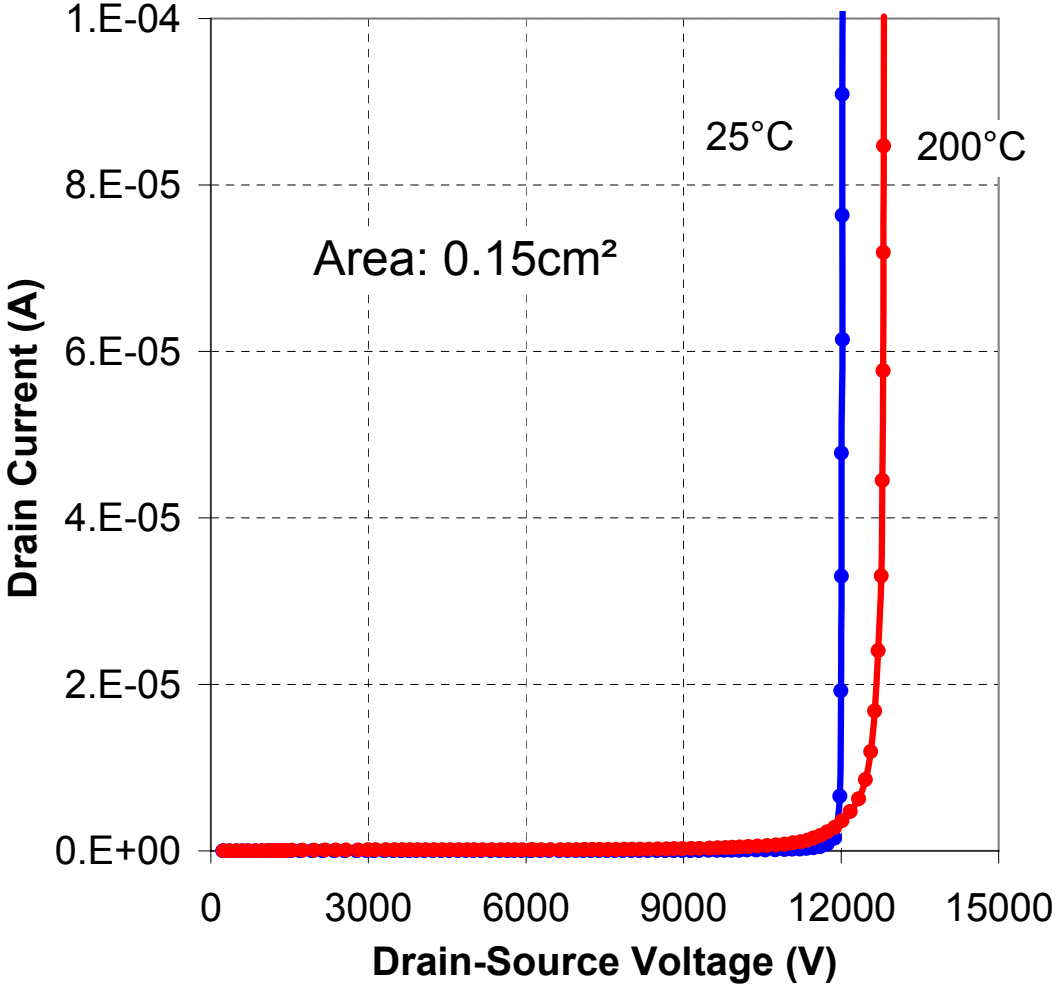
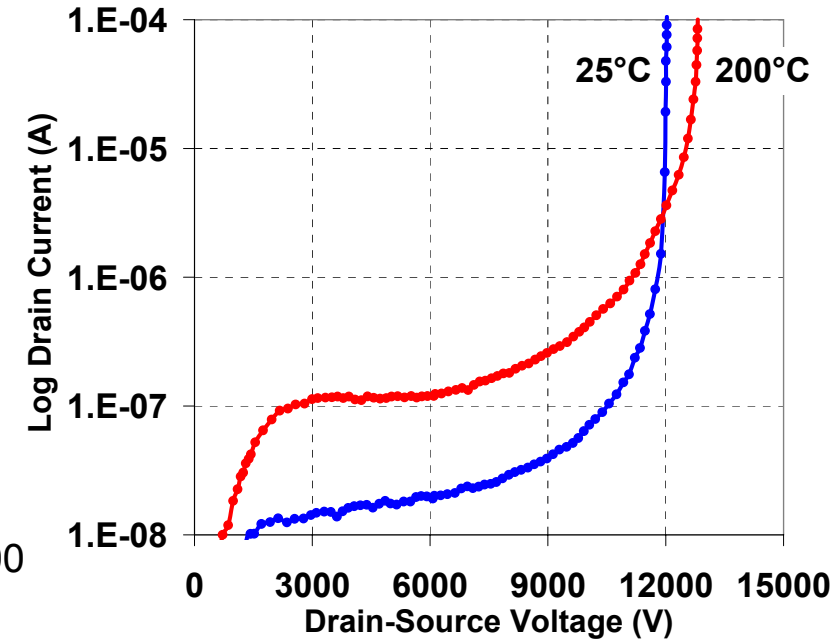
MOSFET Voltage Capability

Voltage Capability > 12 kV



Low Channel Leakage for Vg ≤ 0, T ≤ 200° C

Increased Threshold Voltage



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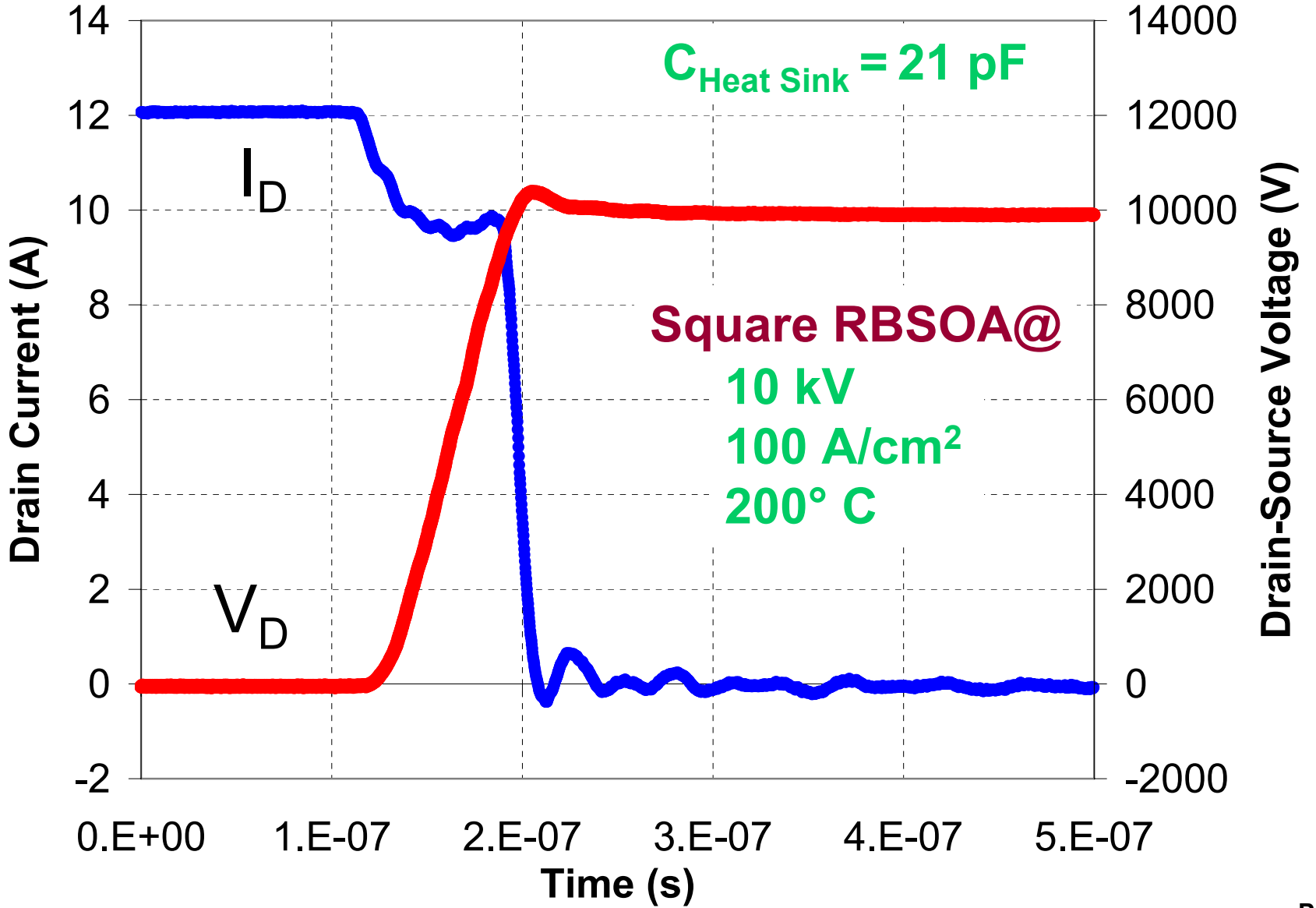
Reverse Bias Safe Operating Area



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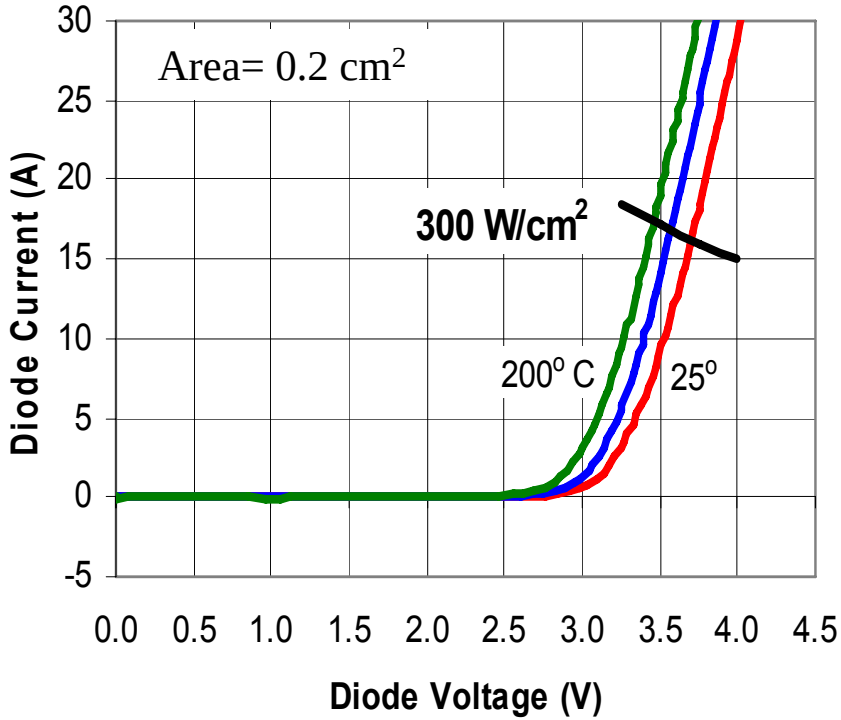
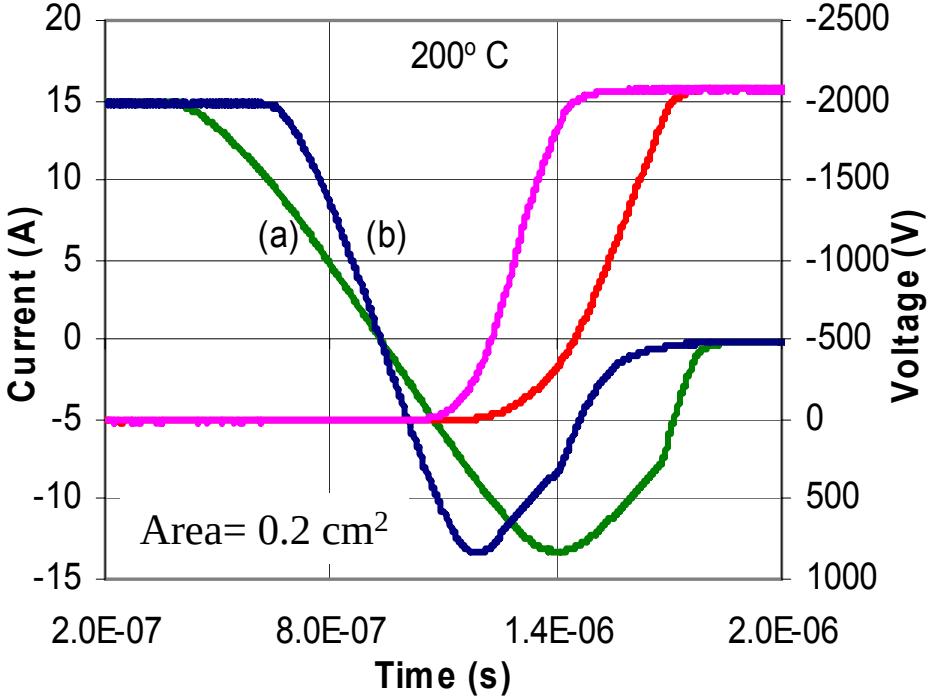
SiC PiN Diode

Continuous Current:
80 A/cm²



Optimizing Speed @ 200 C:
500 ns → 300 ns …



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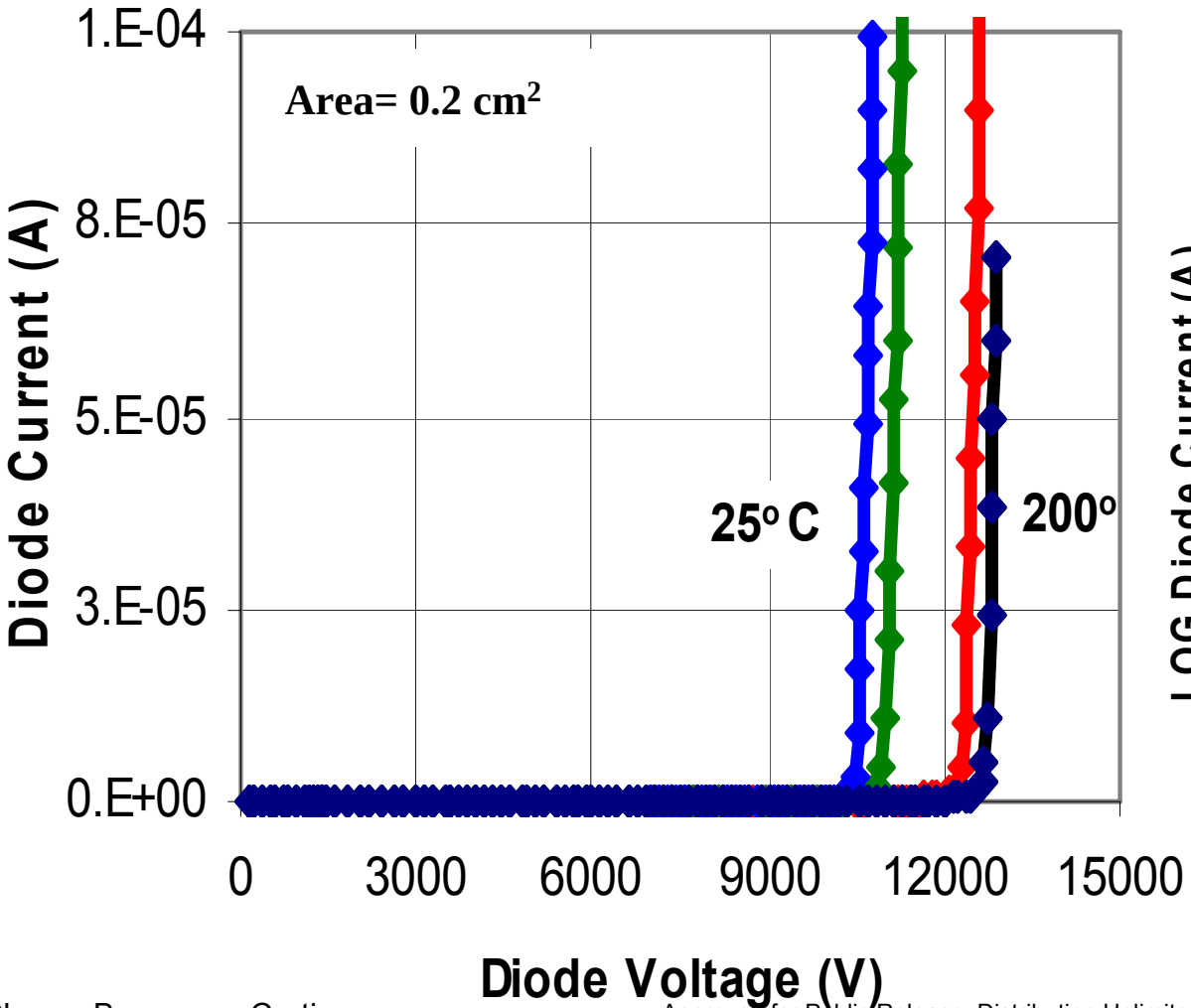
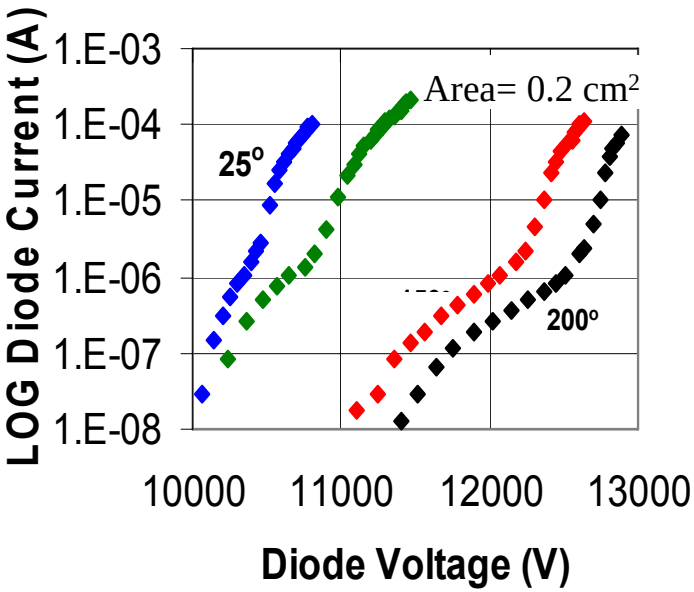
Diode Voltage Capability

Voltage Capability > 10 kV



Extremely Low Leakage: 10 nA for V < 10 kV



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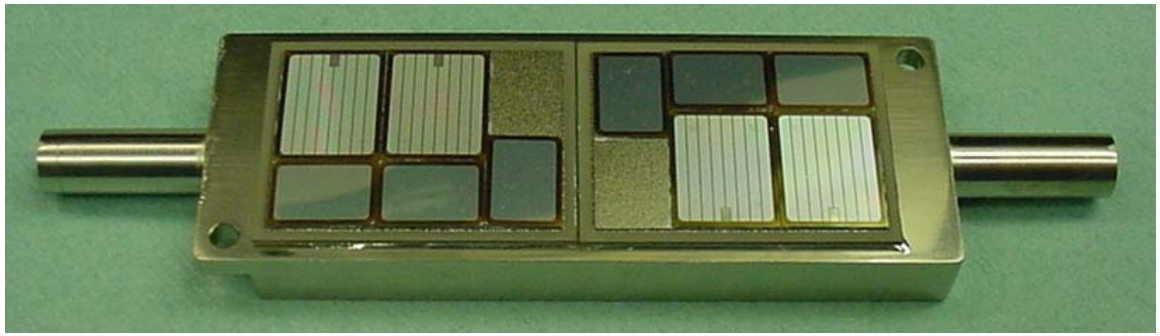
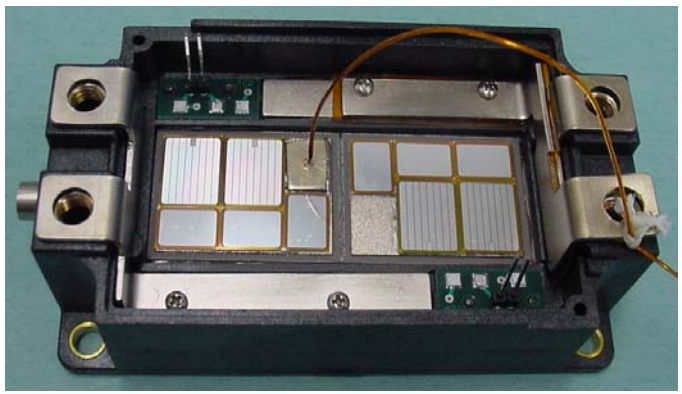
Half Bridge Module Package
10-kV, 110-A, 20 kHz

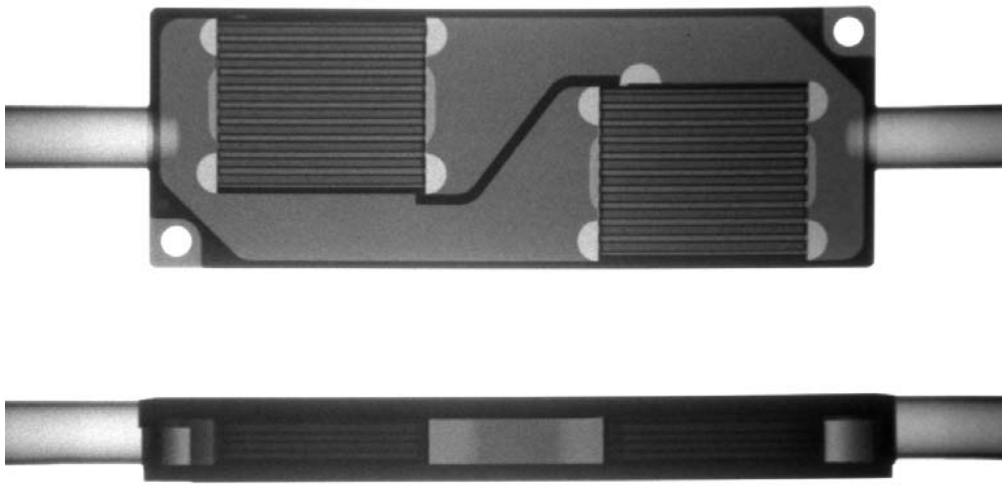
- **Normal flow heatsink for high heatflux**
- **15-kV voltage isolation**
- **High-temperature, high-field potting compound**

Mikronos Normal Flow Heatsink

- **Heat dissipation goal is 500 W/cm^2**
- **Thermal expansion match to SiC**







Application:
Solid State Power Substation

Memorandum of Agreement

Director, DARPA / Chief of Naval Research / PEO-Aircraft Carrier

Approved by:

RADM Dennis M. Dwyer
Program Executive Officer, Aircraft Carriers

RADM Jay M. Cohen
Chief of Naval Research
U.S. Department of Navy

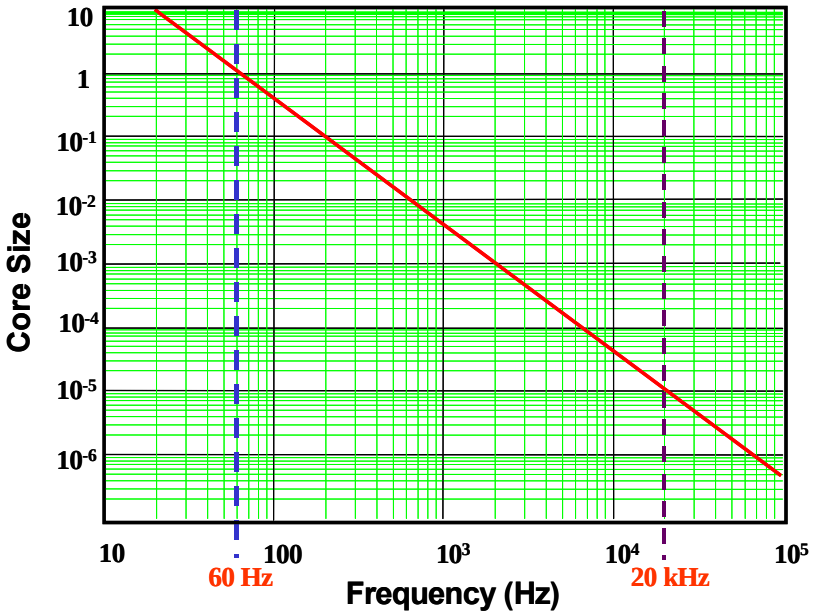
Dr. Anthony J. Tether
Director, Defense Advanced Research Projects Agency
U.S. Department of Defense

Program Technical Milestones

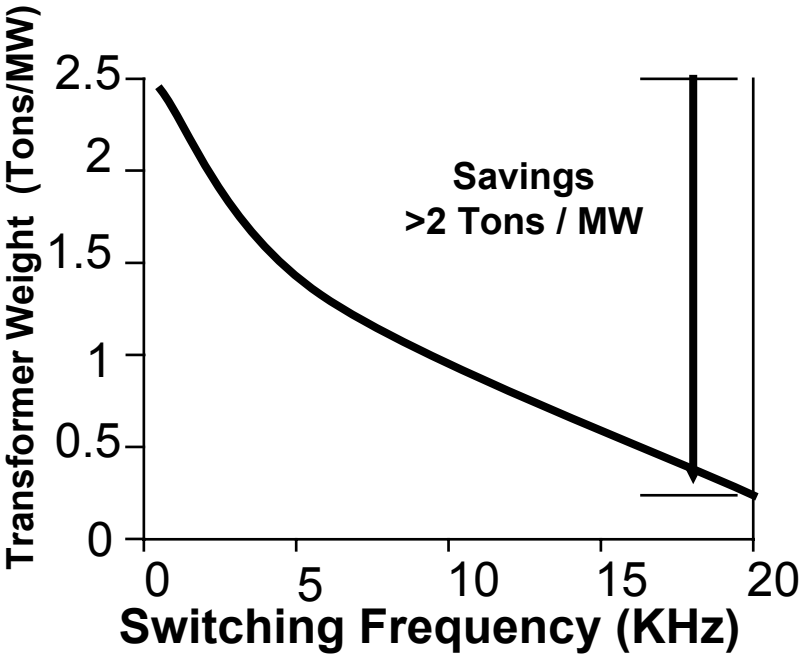
Task	Estimated Completion Date
Phase II **Develop 10-20kV switches (IGBT's, MOSFETS) and PiN diodes. Packaging.**	**3Q FY06**
Phase III **Integrate devices and 20kHz transformer into SSPS 2.7 MVA transformer prototype.**	**3Q FY08**
Phase IV **Demonstrate 2.7 MVA SSPS**	**1Q FY11**

Higher Frequency Positive Ship Impact

- Smaller transformer - size and weight (presently >40% of weight, 15% of the cost of State-of-the-Art PCMs)
- Solid State Power Substation
  - Precise voltage regulation
  - Unity Power Factor (20% increase in power)
  - Fast fault detection, protection, restoration
  - DC Distribution



$$CoreSize \sim \frac{1}{Frequency}$$



Silicon Carbide Reduces Transformer Weight by ~ 2 Tons per Megawatt of Power

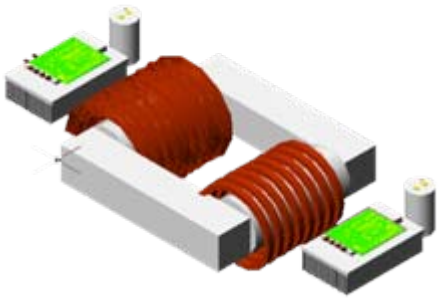
Transformer Application Specifics:

13.8 kV – 450 V Solid State Power Substation (SSPS)

Conventional Approach:
Low Frequency Transformer (analog)

Transformer (~40 on CVN):
- 2.7MVA
- 13.8kV/450V (Δ/Y) 60Hz
- **6 tons/each**
- **10 m³/each**
- **fixed, single output**

SiC-based Solid State Power Substation (digital)



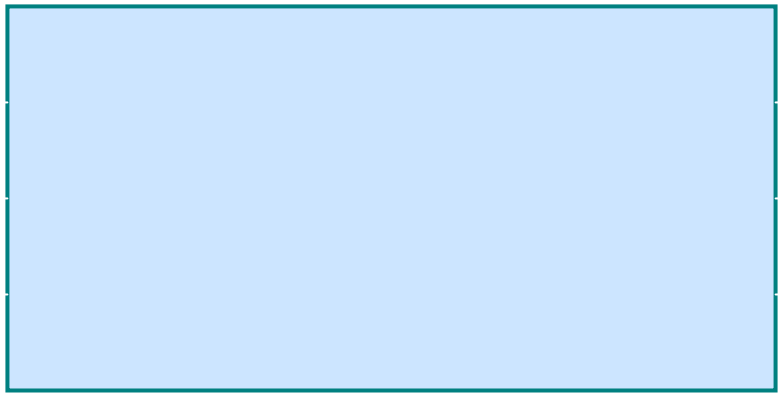
Solid State Power Substation (estimated):
- 2.7 MVA
- 13.8kV/450V (Δ/Y) 20 kHz
- **1.7 tons/each**
- **2.7 m³/each**
- **multiple taps/outputs**

Additional performance features of SiC SSPS
- Precise voltage regulation (sag, flicker, harmonics)
- Operates at Unity Power Factor to source (effective 20% increase in useable power)
- Fast fault detection, protection and restoration (potential to eliminate circuit breaker)
- Easy energy storage
- Enables DC distribution

Total estimated weight and volume savings: 172 tons, 292 m³

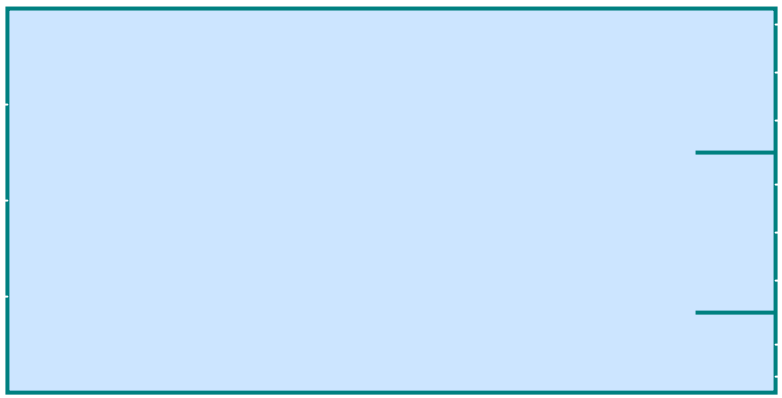
SSPS Inputs and Outputs

13.8 kVac,
3φ, 60Hz



Type I
(450 Vac,
3φ, 60Hz)

13.8 kVac,
3φ, 60Hz



Type I

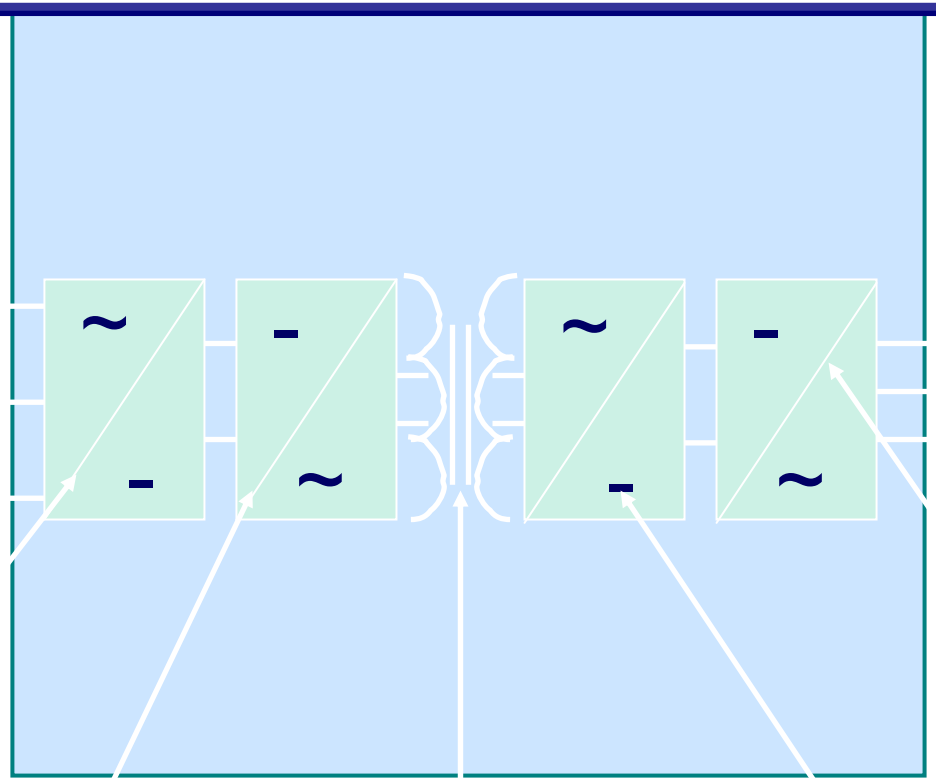
Type III

Vdc (270Vdc)

SSPS Generalized Architecture

'Integral 3φ SSPS'

13.8 kVac,
3φ, 60Hz



Type I

Front End Rectifier

High Frequency Transformer

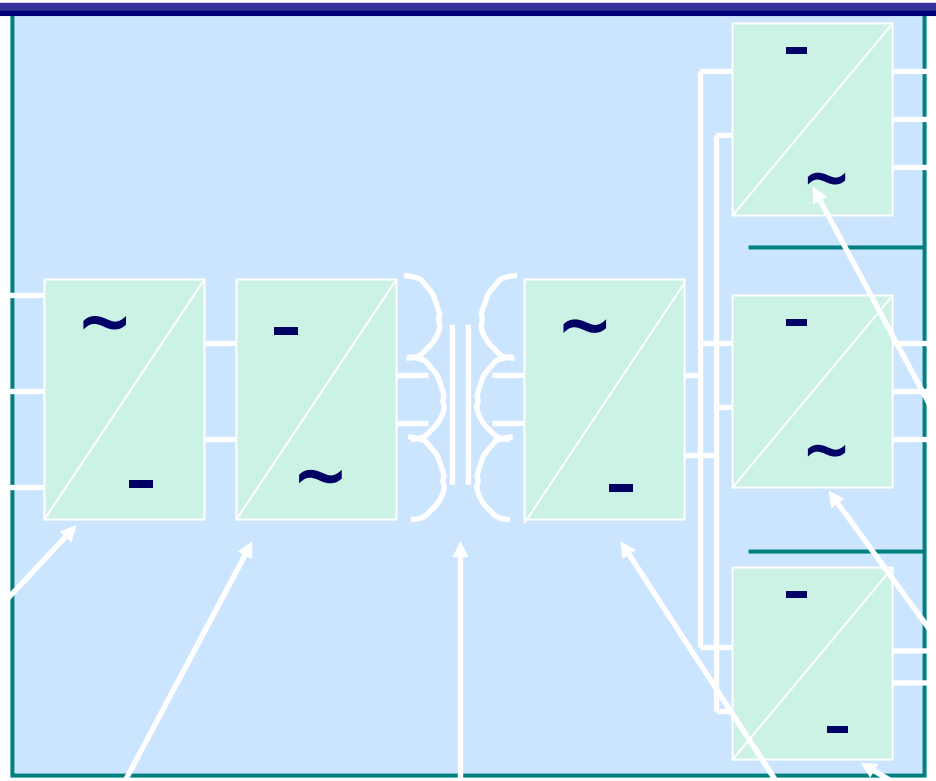
Output Converter

Front End Inverter

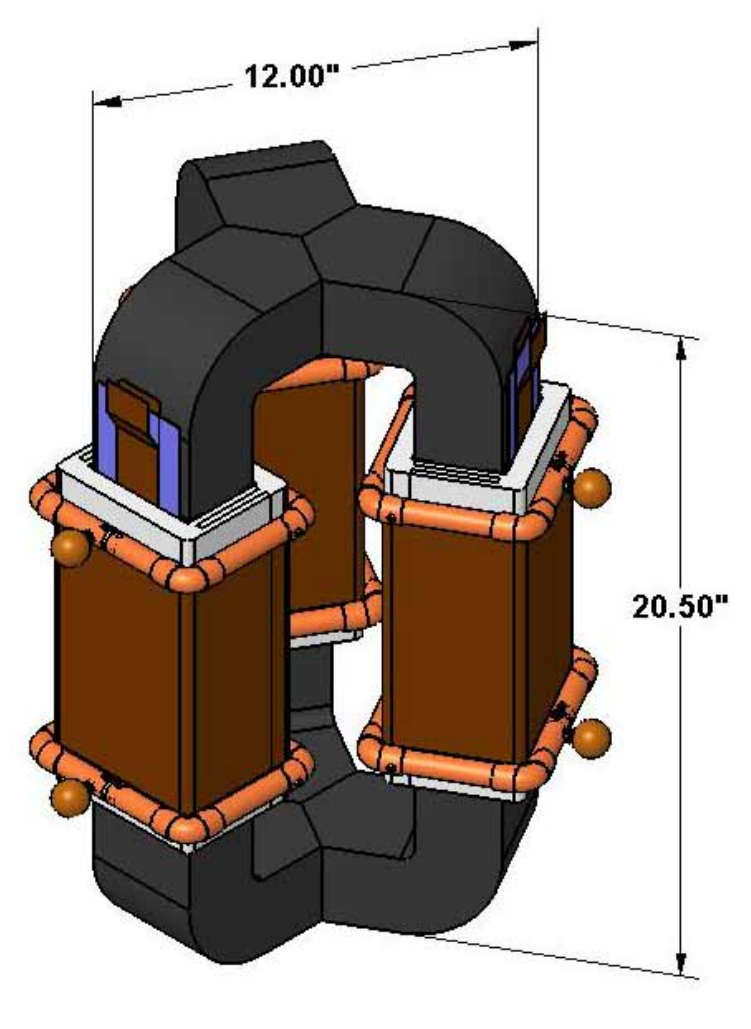
Output Rectifier

SSPS Generalized Architecture

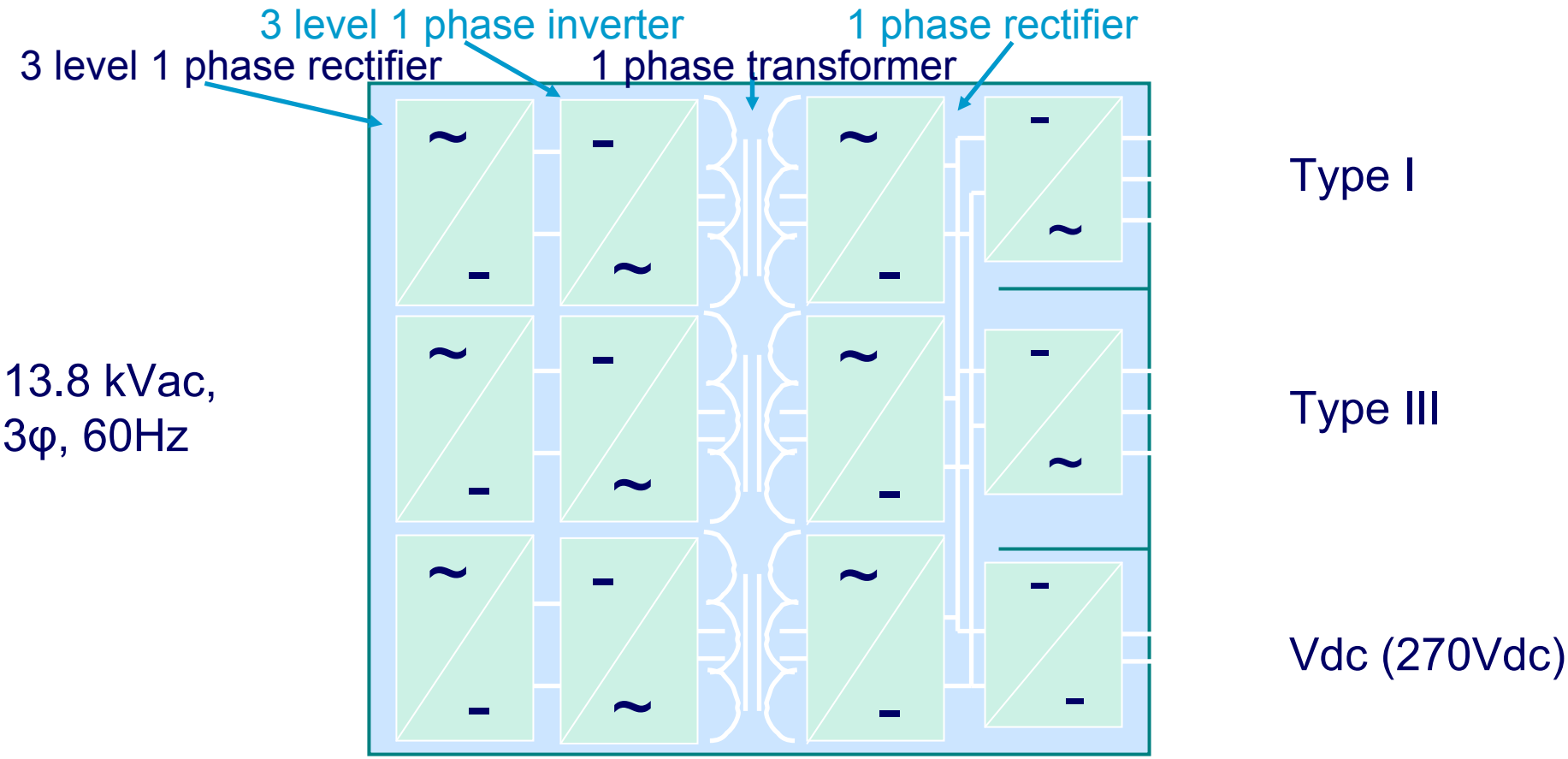
'Flexible Output SSPS'



Polyphase Y (2.7 MVA)



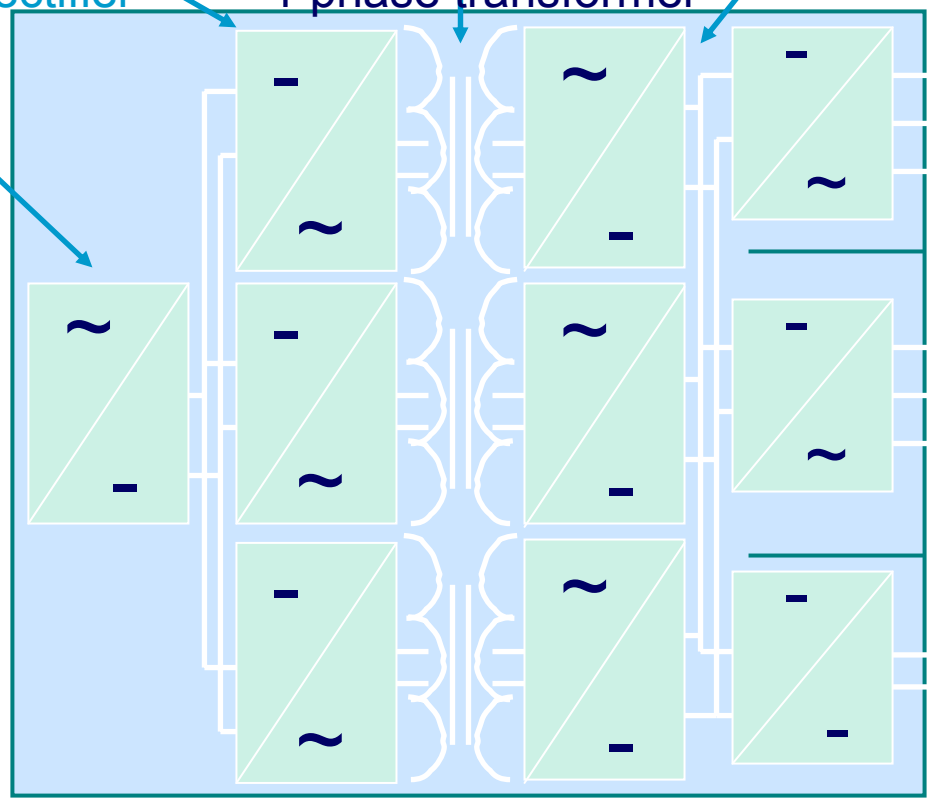
SSPS Design Concept (3 x 1φ)



- It is modular -

Another good thing – redundancy

SSPS Design Concept (1 x 3φ)



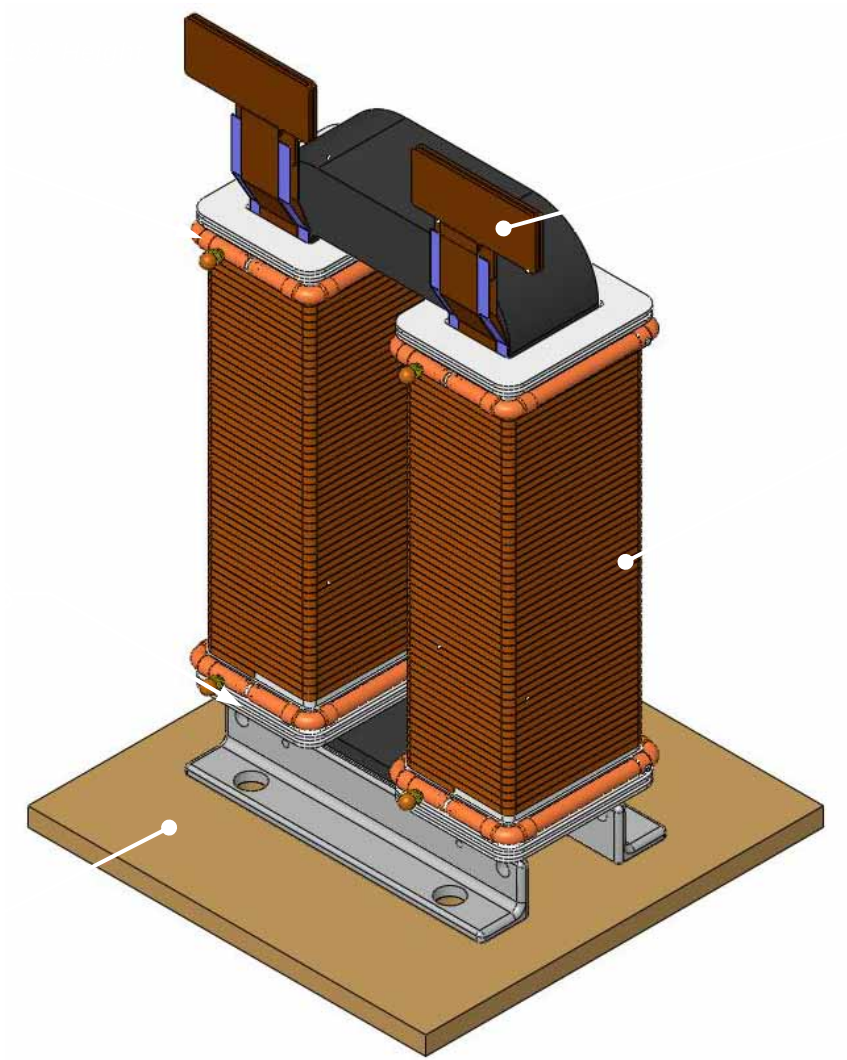
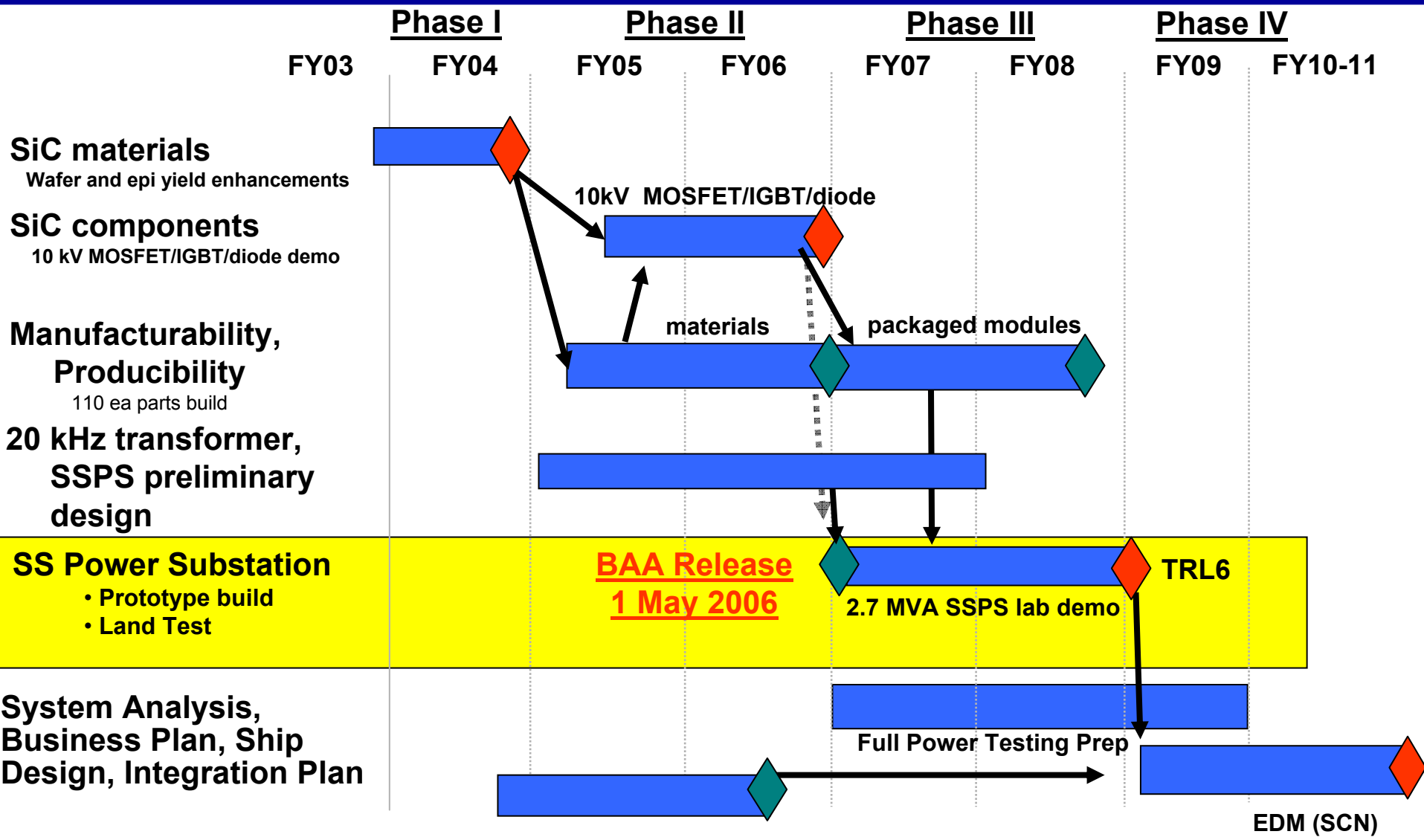
13.8 kVac,
3φ, 60Hz

? 1x3φ or 3x1φ ?

Balanced load to source

Approved for Public Release, Distribution Unlimited

Core Designs Higher Efficiency & Simplicity



Program Timeline