Silicon-Carbide Power Devices for High-Voltage, High-Frequency Power Conversion Applications

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Outline

- Silicon-Carbide (SiC) Power Devices
- HV-HF Power Conversion
- DARPA-HPE SiC Device Development
  - Phase 2 SiC MOSFET: 5-A, 10-kV
  - Phase 2 SiC PiN Diode: 20-A, 10-kV
  - Module Package: 110-A, 10-kV, 20-kHz
- Conclusion

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1) 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
- **<u>Higher voltage, current and speed</u>:** larger breakdown field
- **Fault tolerance, Pulsed:** intrinsic-temperature, saturation-velocity and thermal-conductivity

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SiC Voltage Blocking Layer

- **Order of magnitude higher breakdown field than Si**
  - **1/10th blocking layer thickness**
  - **10 times higher blocking layer dopant density (conductivity)**

➢ **Majority carrier SiC device: 100 times lower resistance**

MOSFET, JFET, Schottky diode

➢ **Minority carrier SiC device: 100 times faster**

$$L = \sqrt{D \cdot \tau}$$

BJT, IGBT, Thyristor, PiN Diode, (DARPA-HPE PIN diode & IGBT)

➢ **Replace slow Silicon minority carrier device with fast SiC majority carrier device**

SiC Schottky replacing 600-V Silicon PiN, (DARPA-HPE MOSFET)

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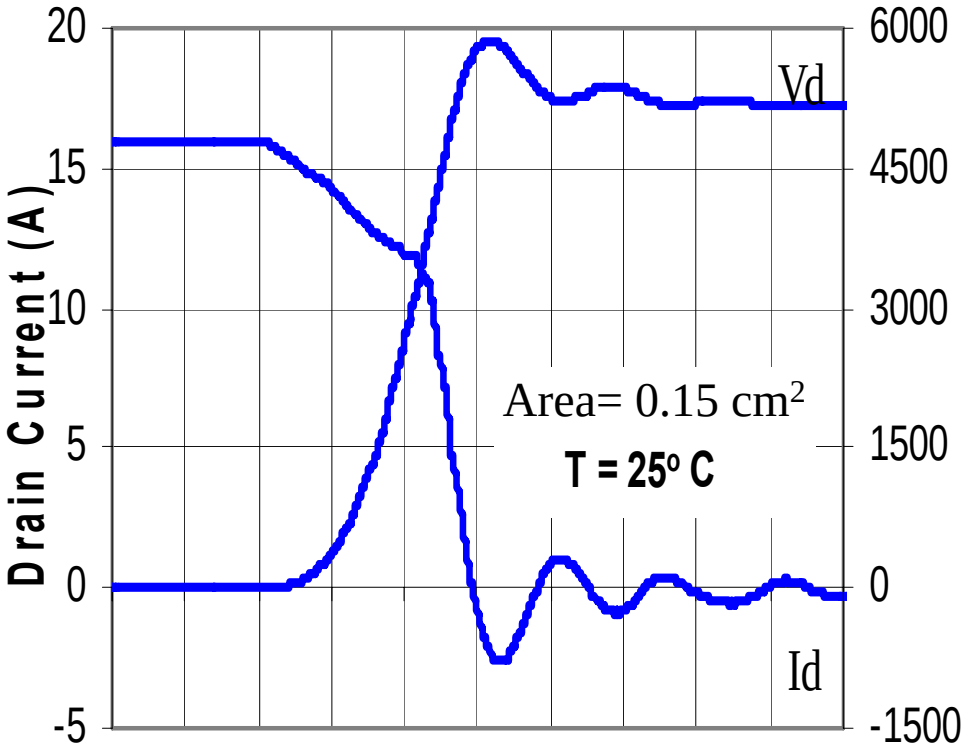
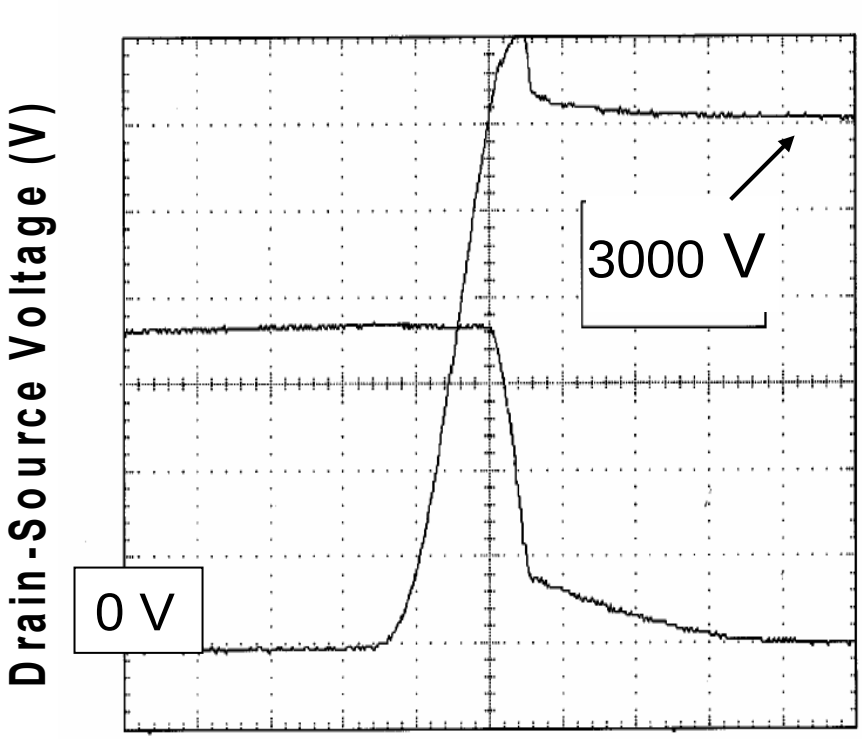
DARPA HPE MOSFET:
High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns



15 ns /div

Silicon IGBT: 4.5 kV, 2us



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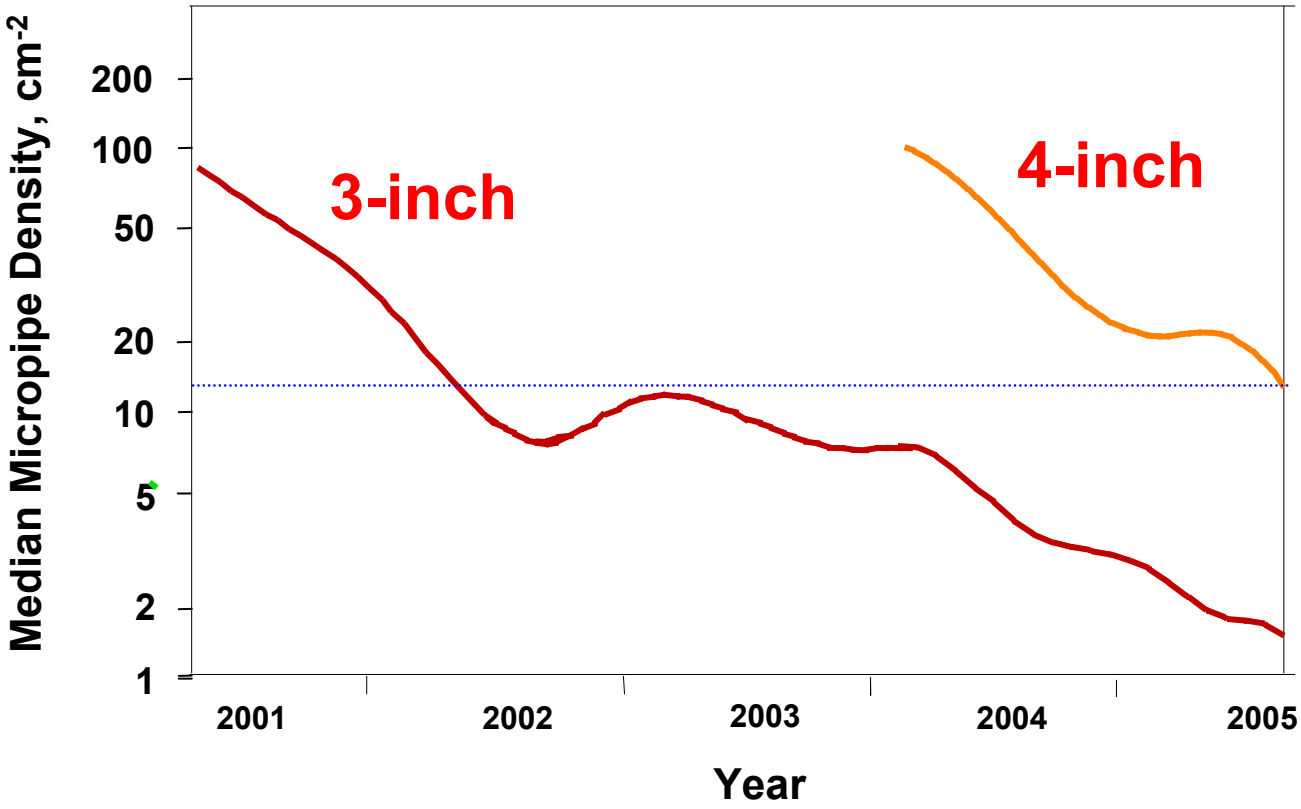
Ongoing Improvement in 4H-N SiC Substrate Quality

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



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2) HV-HF Power Conversion

- **Switch-mode power conversion and conditioning:**
  - **efficiency, control, functionality, and weight**
  - **applications from: 100 V @ MHz to 6 kV @ kHz.**
- **New semiconductor devices extend application range:**
  - **1990's: Silicon IGBTs**
    - **higher power levels for motor control and traction**
  - **Emerging: SiC Schottky diodes and MOSFET**
    - **higher speed for power supplies and motor control**
  - **Future: HV-HF SiC MOSFET, PiN diode, and IGBT**
    - **enable 15-kV, 20-kHz switch-mode power conversion**

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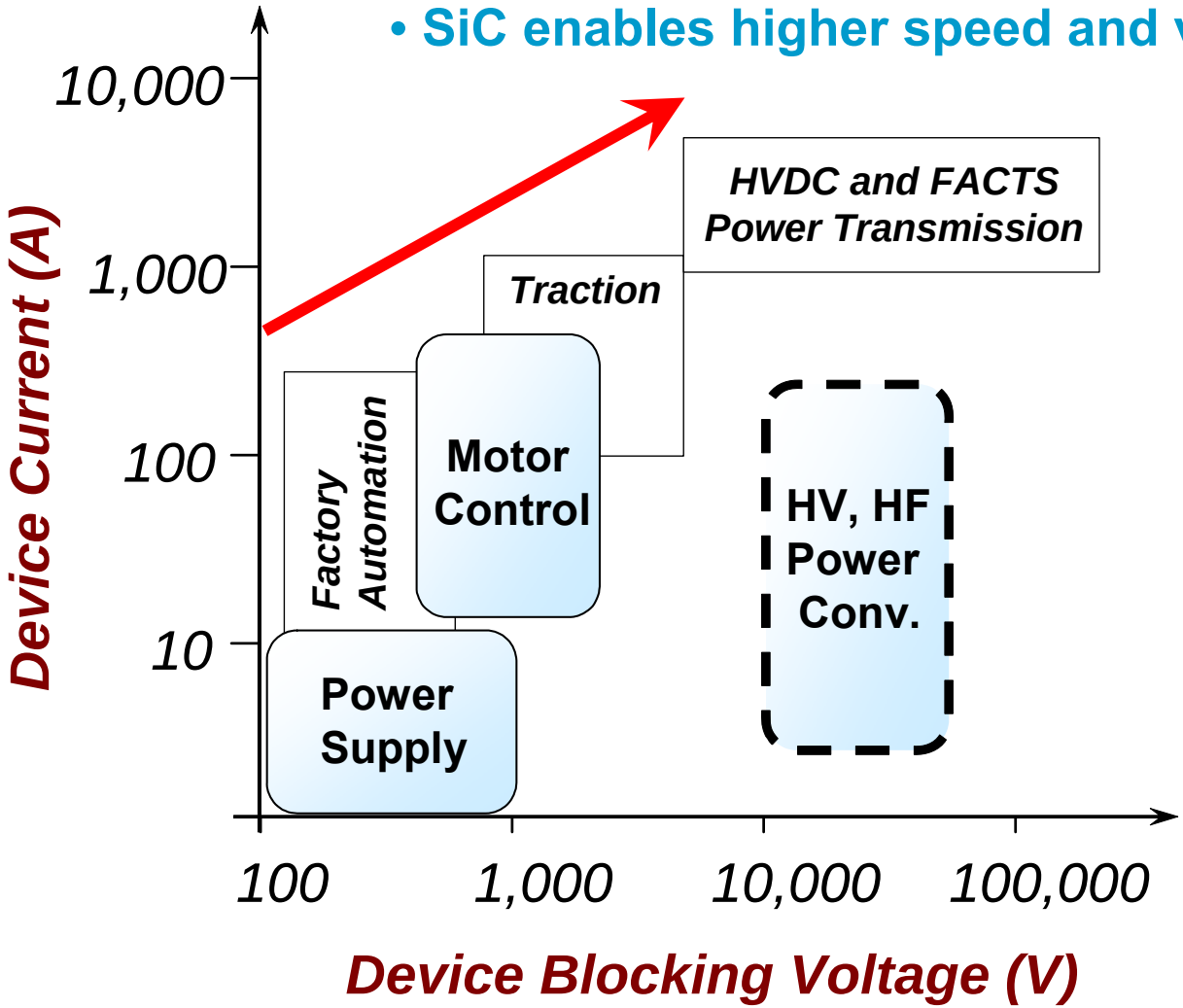
Switching Power Applications

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



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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

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3) HPE SiC Device Development

- **Driving force spearheading development of HV-HF SiC devices is DARPA WBG HPE program:**
  - **Phase 1 (completed 2004): demonstrated underlying material and device capability**
  - **Phase 2 (began 2005): focused on developing reliable device technology for SSPS**

DARPA High Power Electronics Proposed Device Development				
	PiN Diode (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**	*25 A*	**110 A**
Tj (°C)	**200 C**	**200 C**	*200 C*	**200 C**
Fsw (Hz)	**20 kHz**	**20 kHz**	*20 kHz*	**20 kHz**

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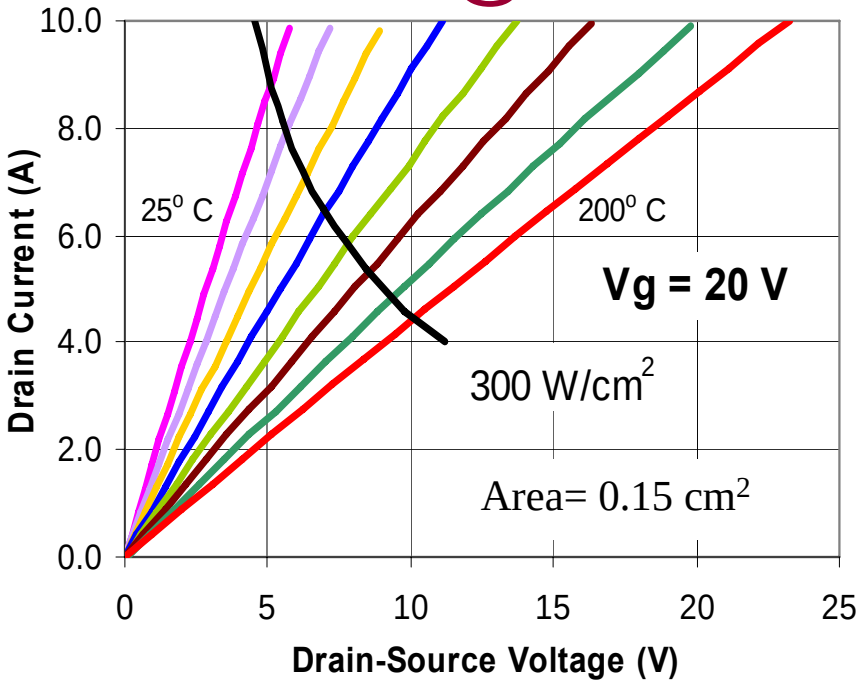
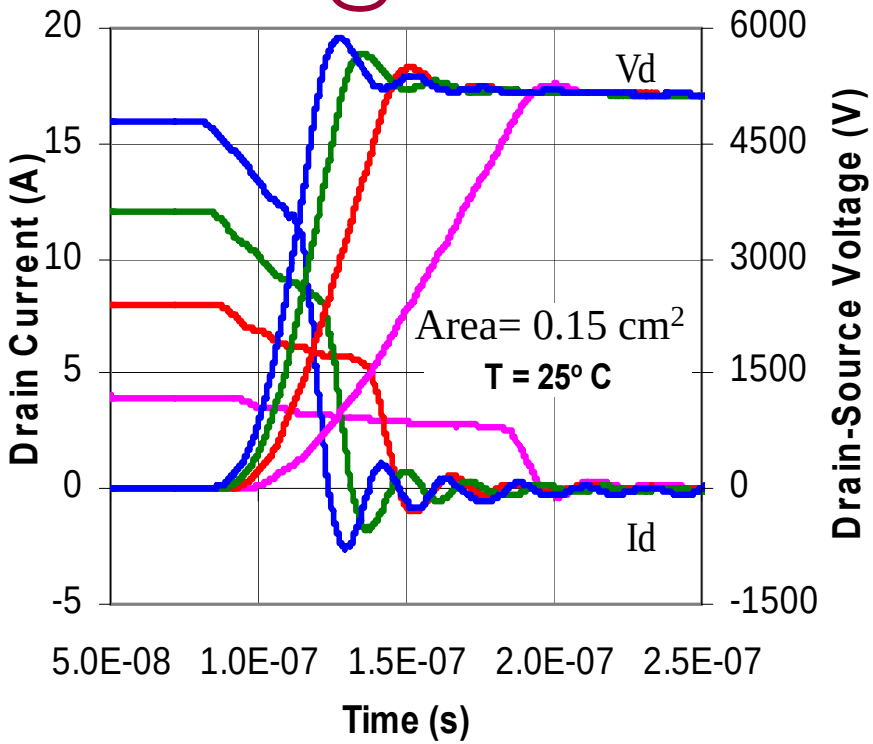
3a) HPE Power MOSFET

Continuous Current: 30 A/cm² @ 200 C



Extremely Fast Switching: 30 ns @ 120 A/cm²



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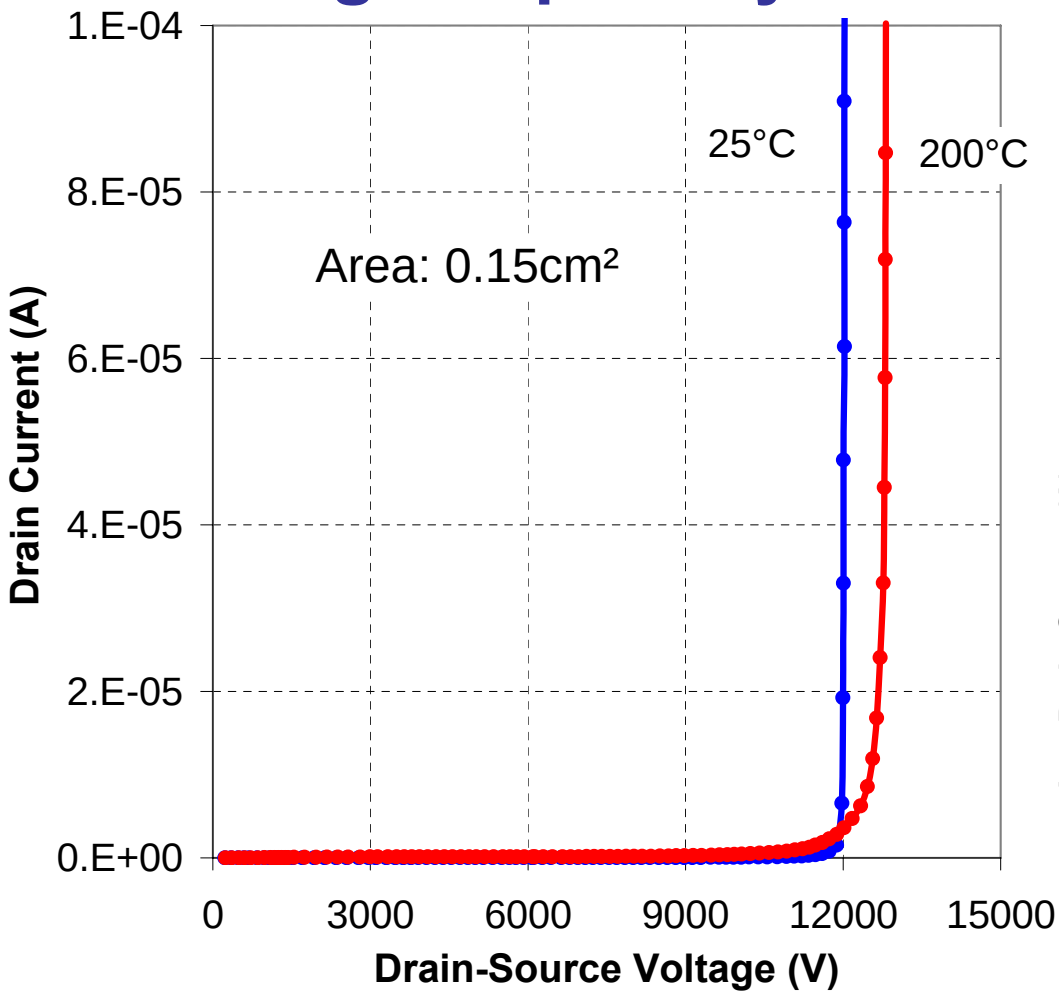
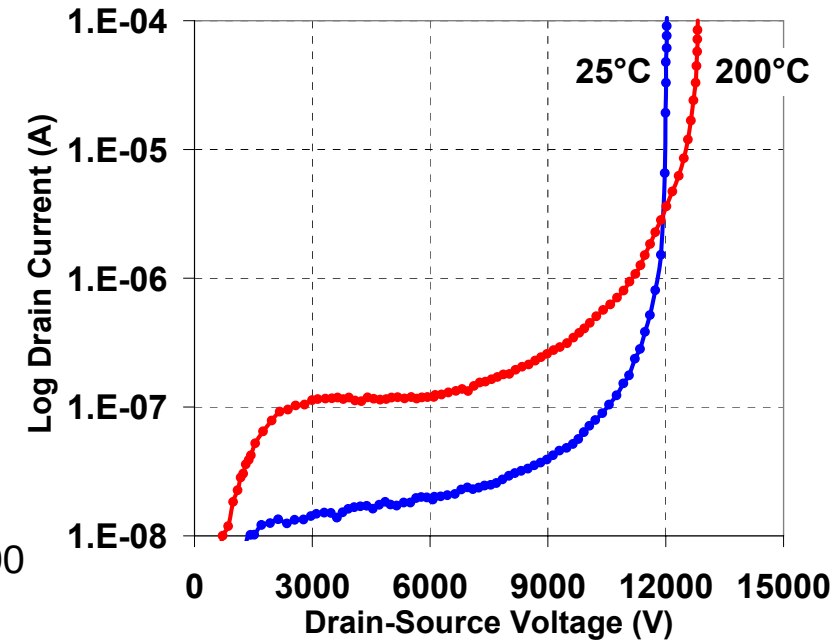
MOSFET Voltage Capability

Voltage Capability > 12 kV



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

Increased Threshold Voltage



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MOSFET Performance Progress

Saturation region parameters extracted from SATMSR program								
	I_{RMS}	A (cm^2)	K_P	K_P /A	K_{P1}	V_T	dV_{TL}	V_{T1}
HPE-1 A	1.0A	0.048	0.038	0.8	1.36	1.0	1.6	-0.013
HPE-1 C	1.5A	0.048	0.142	3.0	0.99	2.4	1.1	-0.015
HPE-2	5A	0.15	0.323	2.1	0.99	4.5	1.6	-0.011

- **High Peak Current:**

  100 A/cm² for Vgs = 15 V

$$I_{Peak} = \frac{K_P}{2}(Vgs - V_T)^2$$

- **No Channel Leakage for Vgs=0:**

  V_{TL} > 0 @ 200 C

$$V_{TL}(T) = V_T - dV_{TL} + V_{T1}(T - 25C)$$

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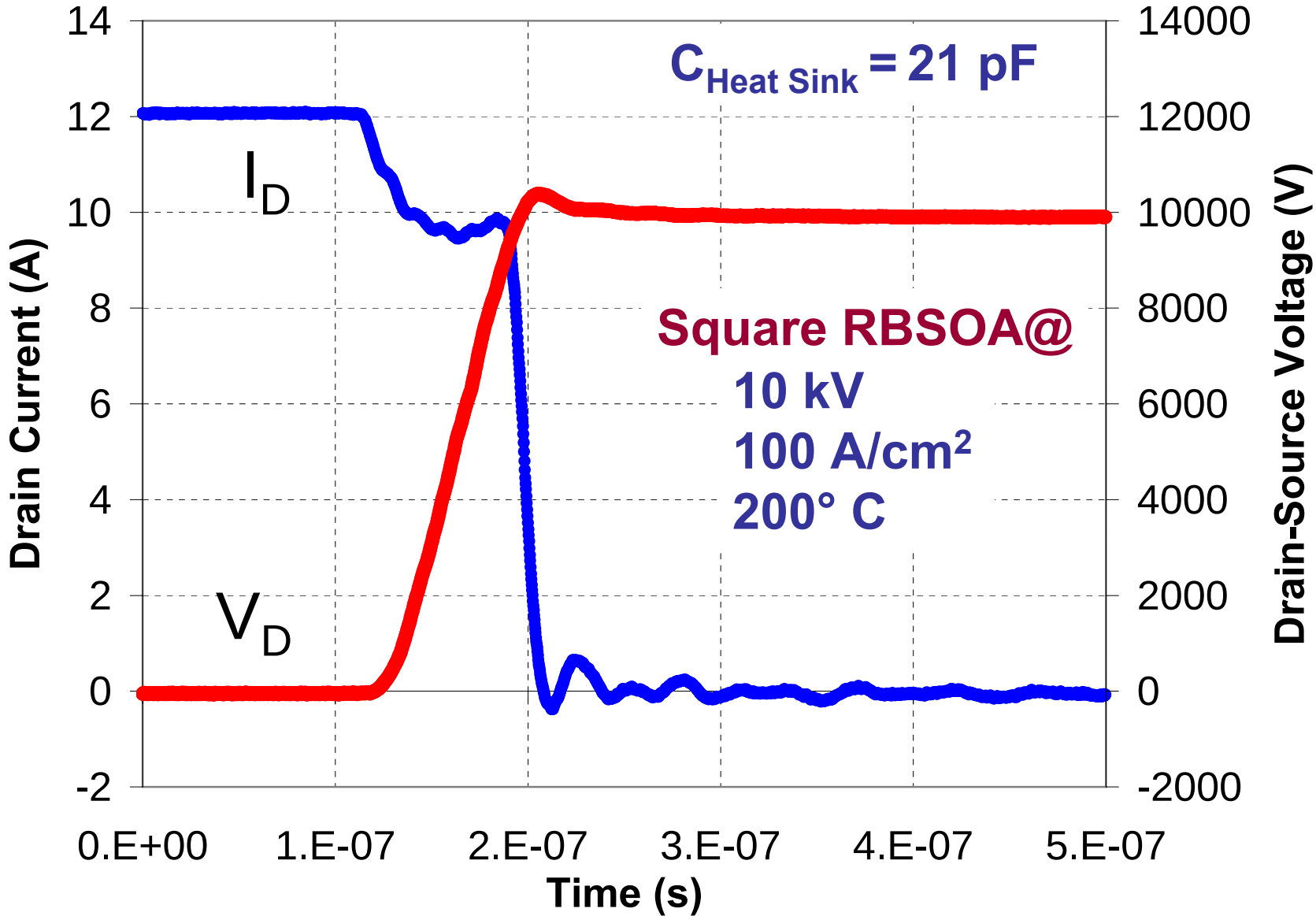
Reverse Bias Safe Operating Area



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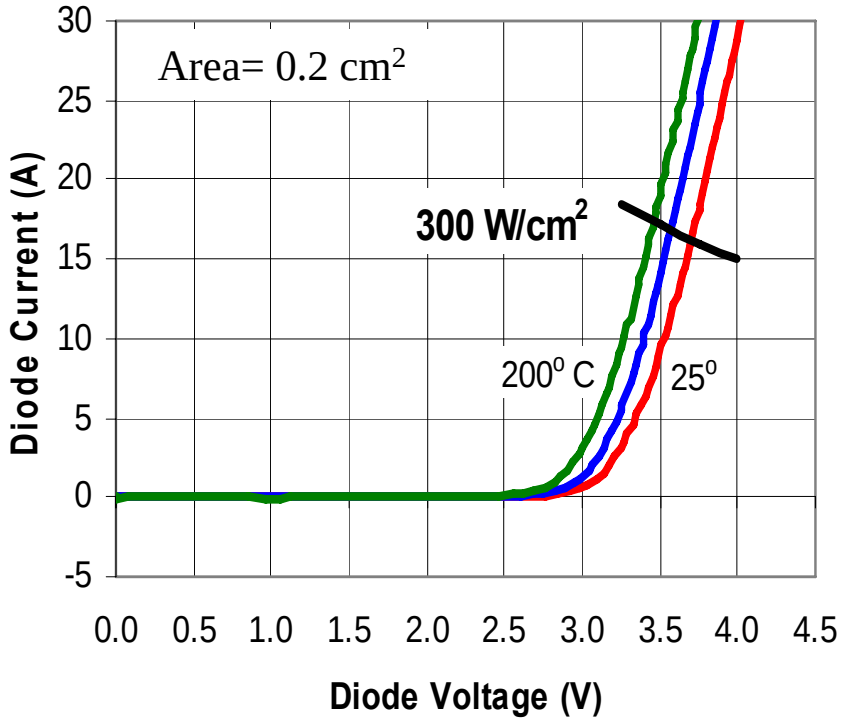
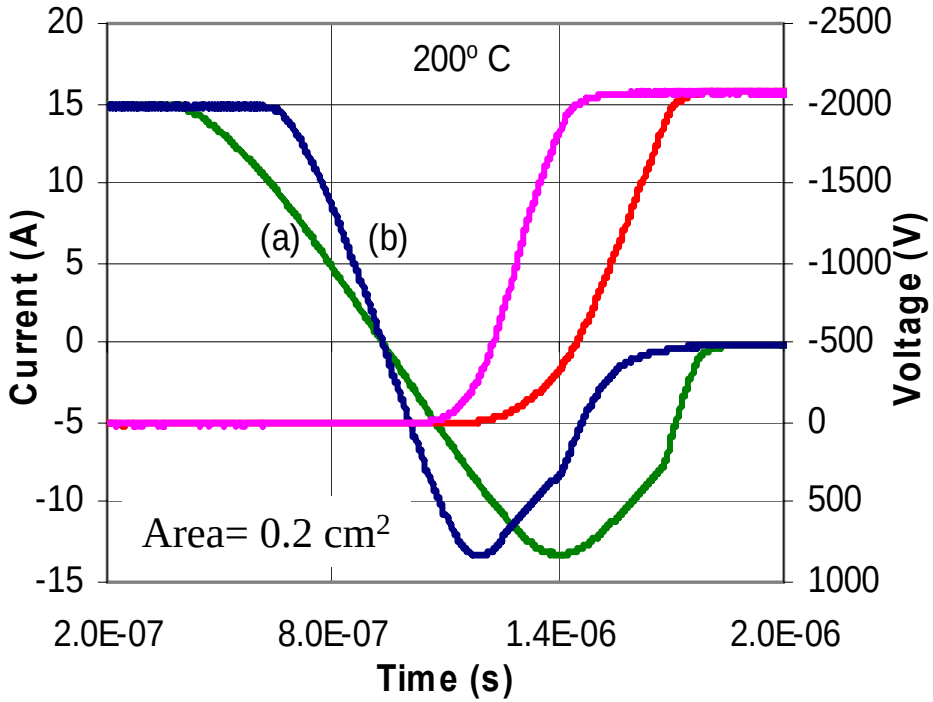
3b) HPE SiC PiN Diode

Continuous Current: 80 A/cm²



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



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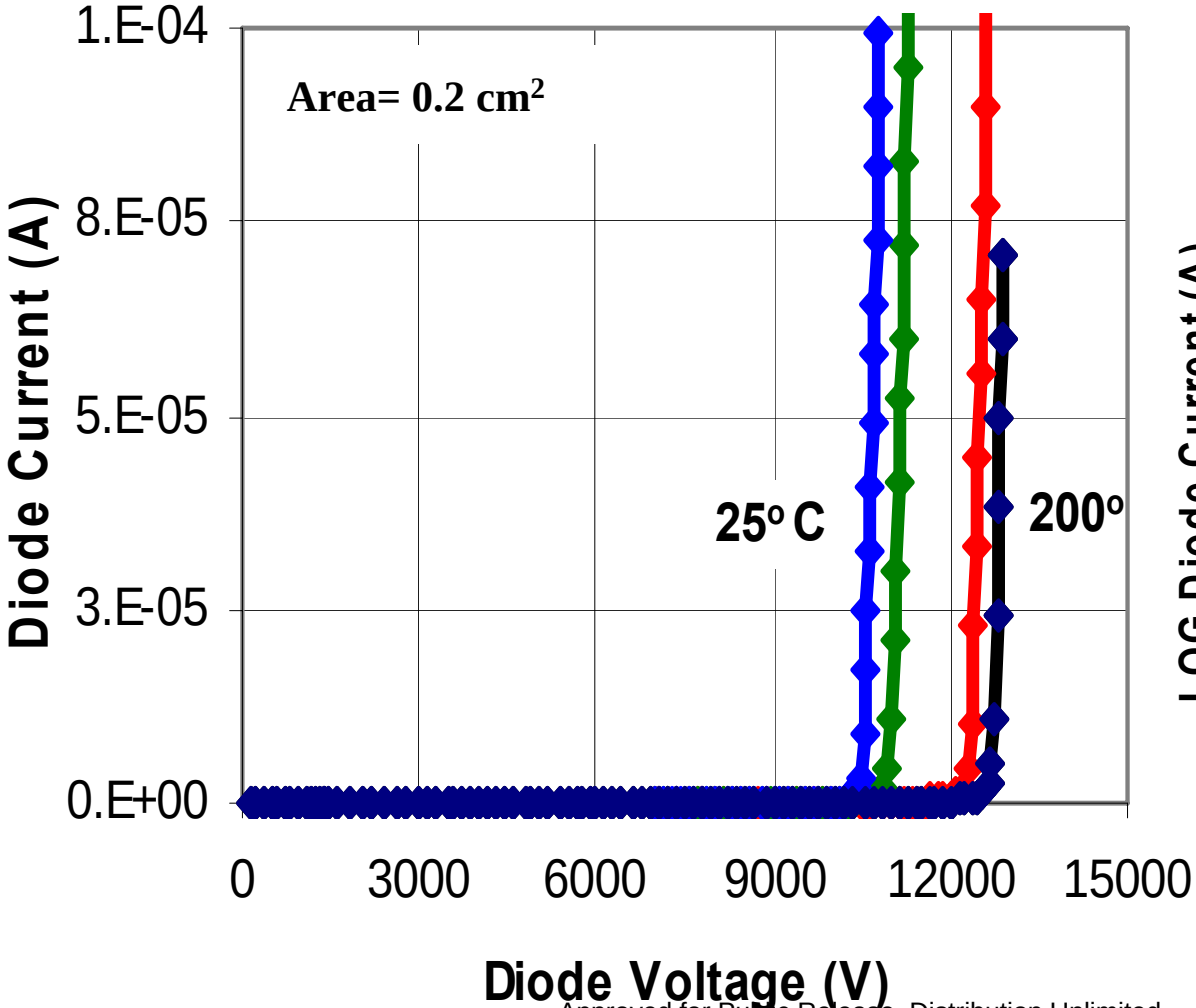
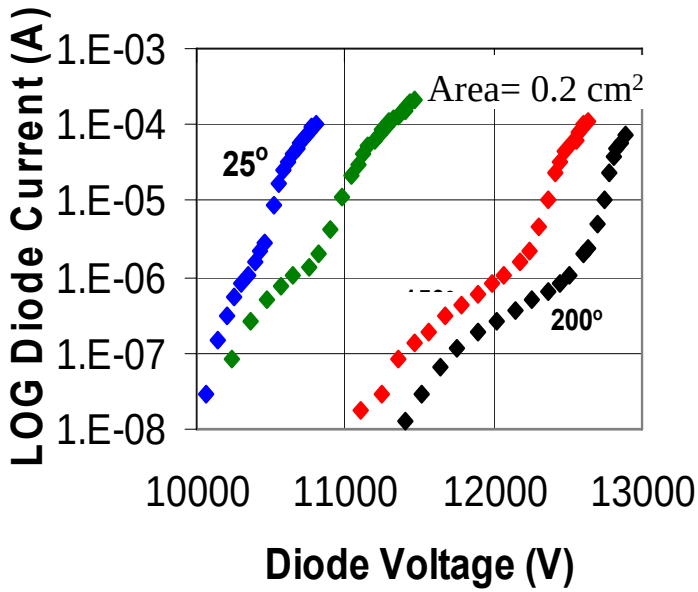
Diode Voltage Capability

Voltage Capability > 10 kV



Extremely Low Leakage: 10 nA for V < 10 kV



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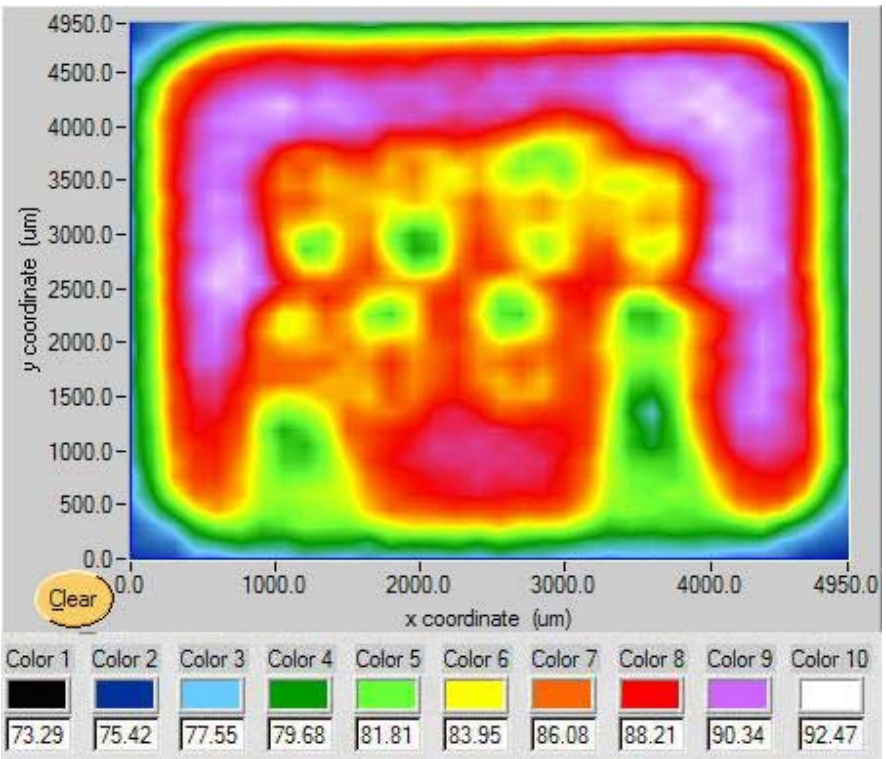
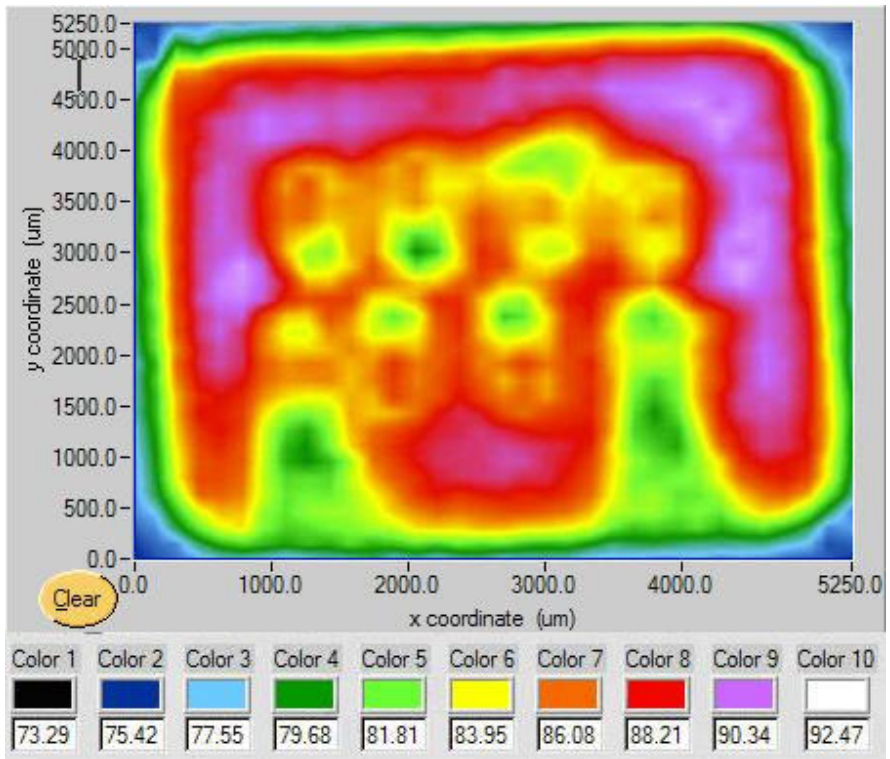
Current Uniformity Improvement

Phase 2 Diode

Before Forward Bias Stress



After 1000 hour stress



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3c) Half Bridge Module Package
10-kV, 110-A, 20 kHz

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

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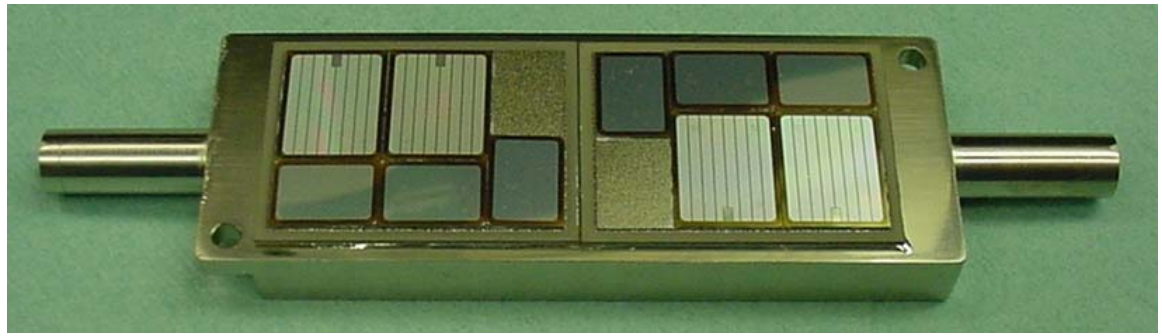
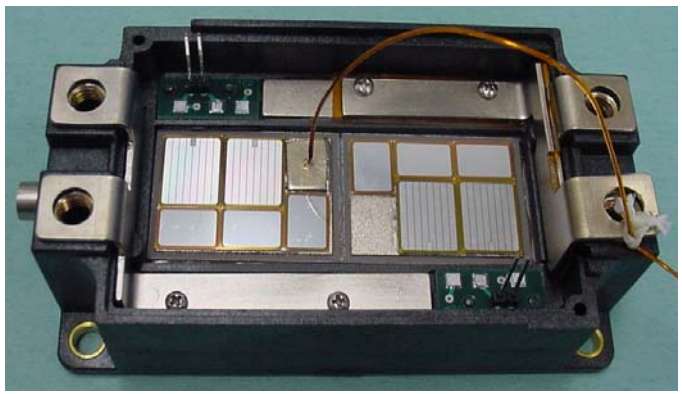
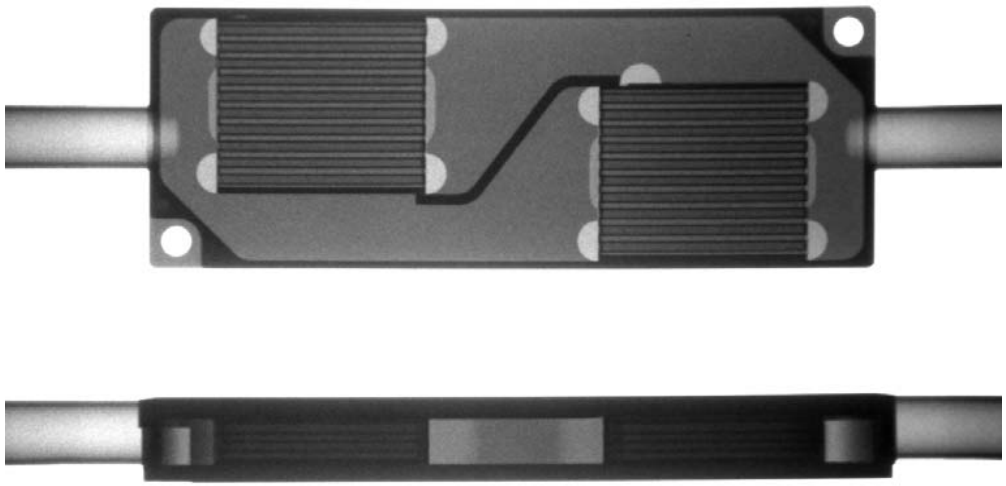
Mikronos Normal Flow Heatsink

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







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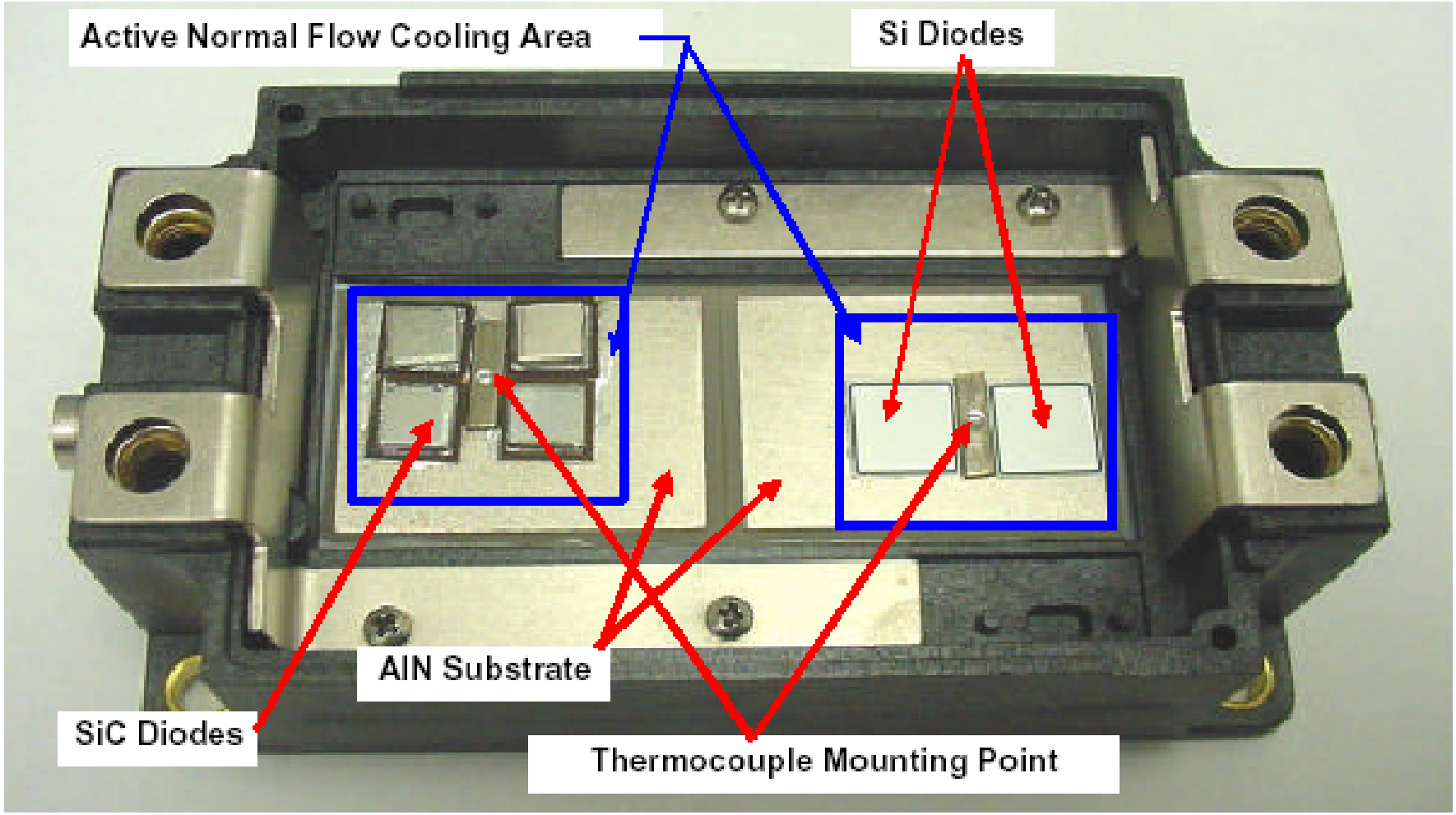
Half Bridge Module Test Vehicle



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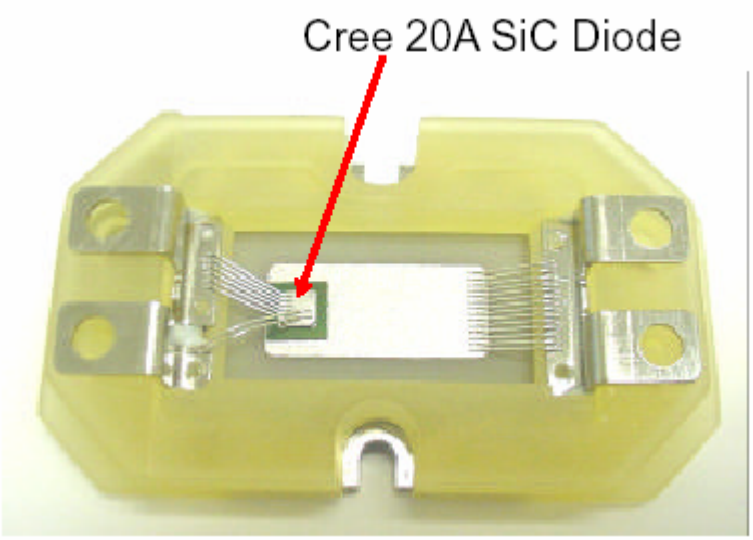
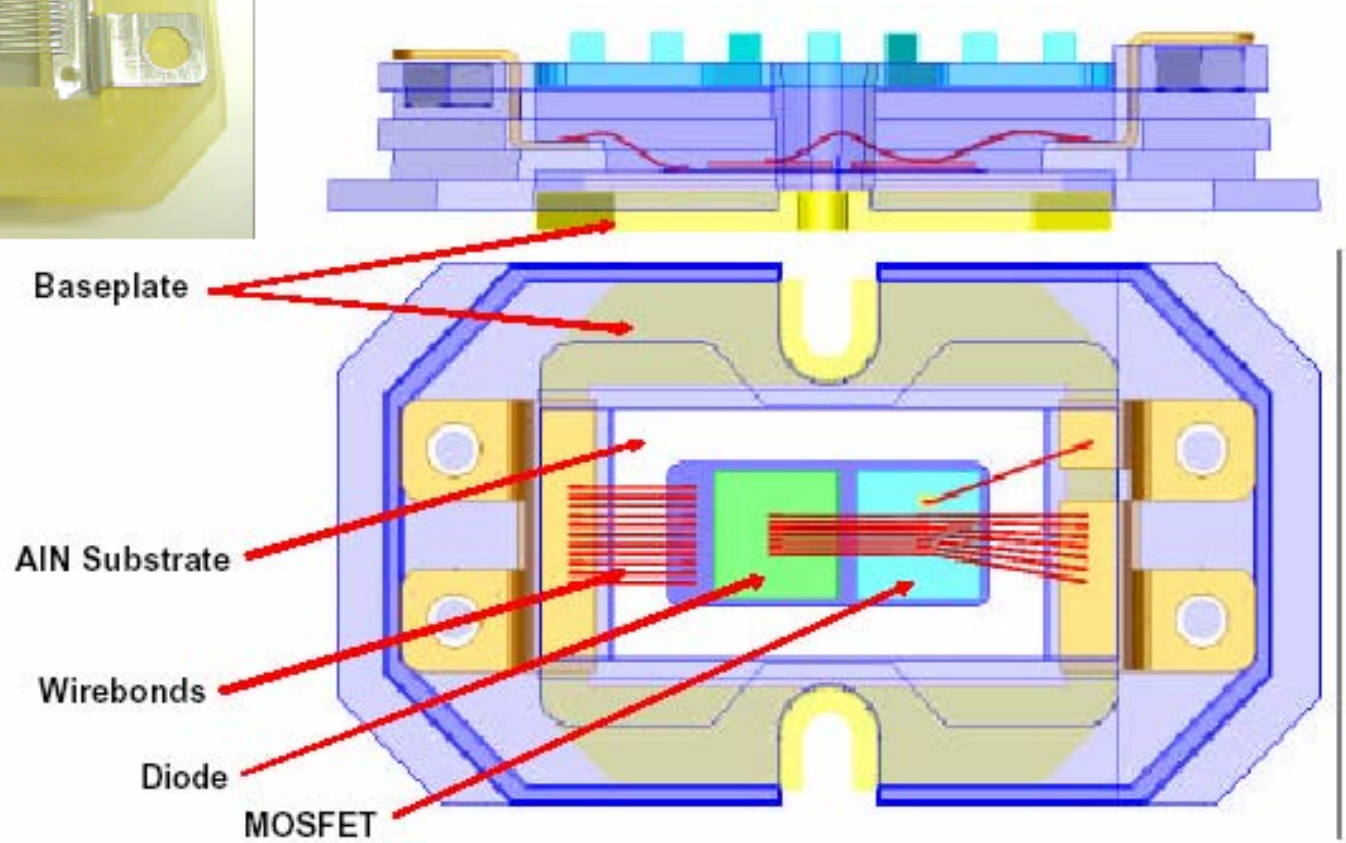
Voltage Isolated Discrete Package



- **Government deliverables**
- **15-kV DBC Voltage Isolation**



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4) Conclusion

- SiC material and fabrication enable HV-HF devices
- HV-HF switch-mode power conversion improves: efficiency, control, functionality, and weight
- DARPA HPE spearheading HV-HF device development
  - ✓ MOSFET: 5 A, 10 kV, and 50 ns switching time
  - ✓ PiN diode: 20 A, 10 kV, and 300 ns reverse recovery @ 200 C
  - – goals include 110 A, 10 kV, 20 kHz half-bridge module
- Further development required for:
  - ➢ Diode forward bias degradation and area uniformity
  - ➢ Diode reverse recovery speed optimization
  - ➢ High current: area scaling and paralleling
  - ➢ Package: high field potting compound @ 200 C

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