Status of SiC Power Devices for Compact High-Efficiency High-Temperature Power Circuits

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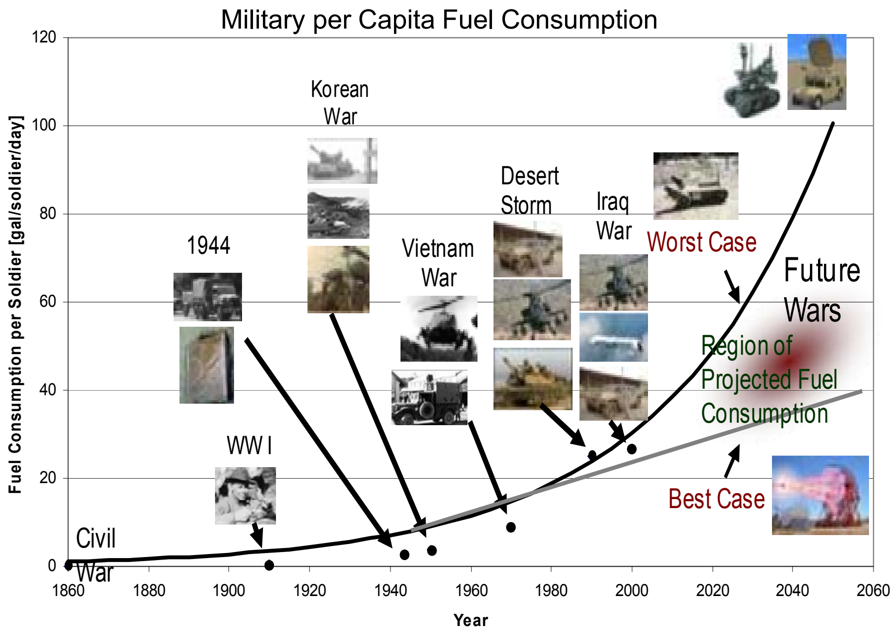
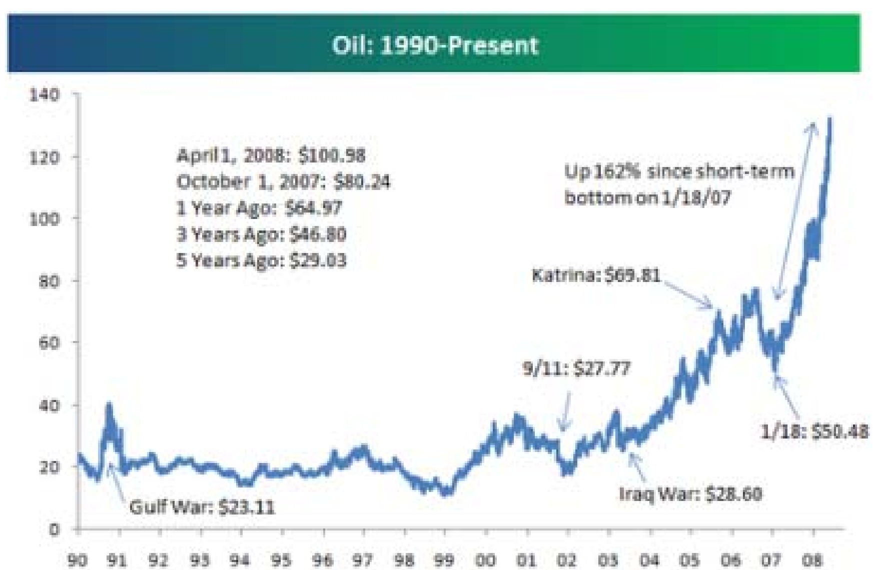
Outline

- Army Platform Power Requirements and Motivation for SiC Power Device Research
- Status of Continuous SiC Power Devices
  - ✓ Technology Background
  - ✓ Results of 1,000 hr Power Module Evaluation
  - ✓ Future Plans
- Status of Pulse SiC Power Devices
  - ✓ Technology Background
  - ✓ Pulse Power - Results of 1,000 shot Evaluations
  - ✓ Future Plans
- Summary

Army Power Problem

- ***Power loads continue to rise on all military platforms. Mission Capability on current and future platforms is driven by effective use of electric power.***
  - ***Deficiency - Limited Space/Payload available to provide power without compromising mission load payload allocation***
  - ***SiC-based converters provide greater power density and finer control than Si-based converters – however maturity /reliability and cost is still a risk factor to PMs.***
  - ***Focus on increased efficiency and temperature for size reduction and fuel economy***





Power & Energy Application Regimes

DOMAINS:

Soldier, C4ISR	C4ISR, Air, Ground	Ground, Effects
MicroWatts to 10s of Watts	100s of Watts to 100s of kW	Up to 1000s of MW

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

SiC Power Electronics
Army Benefits

Reduced SWAP, reduced cooling requirements, increased efficiency at high voltage and higher operating temperatures. Overall, easier to integrate onto military ground vehicles than silicon based systems and provide significant deltas in fuel economy and mobility performance.

Category	Army Fuel Consumption (M gal / yr)	
	Peacetime OPTEMPO	Wartime OPTEMPO
Combat Vehicle	**30**	**162**
Combat Aircraft	140	307
Tactical Vehicle	**44**	**173**
Generators	**26**	**357**
Non-Tactical	51	51
Total	291	1040

Def. Sci. Board Task Force on DoD Energy Strategy Report (2008, pg. 41)

- **Size / Weight:** Up to 2X smaller and lighter compared to Si circuits.
- **Power:** 70 % more efficient than Si Circuits and, hence, 1- 3 % fuel savings for mechanical-drive platforms and even greater for HEVs (operated at ≤ 3 MPH).
  - **For 2% efficiency increase in combat vehicles alone, savings could be $648 M/yr during wartime OPTEMPO; additional 3X in savings could be realized when you include Tactical Vehicles and Generators.**
- **Cooling:** greater operating temperature (>100°C coolant) and high efficiency, cooling system SWAP is significantly reduced.
- **Reliability:** Si power electronics (80°C coolant) have no thermal margin. SiC power electronics (100°C coolant) have >60°C margin and can provide **'Limp Home' functionality**.
- **Endurance:** ability to sustain operations for an extended time without support or replenishment.

Power Electronics
High Temperature Requirements

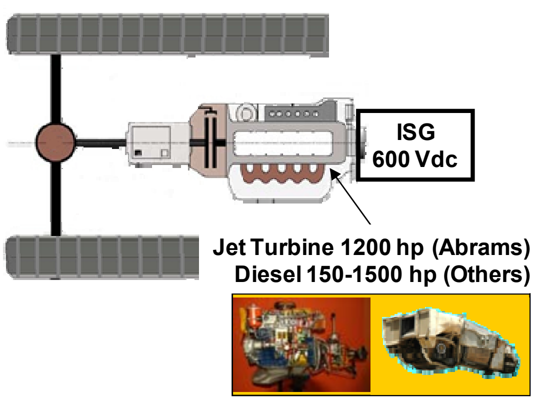
- Current acquisition programs allow separate coolant loops for power electronics ranging from 30°- 70°C
- Next-Generation vehicles will reduce the number of vehicle cooling loops; power electronics would be cooled at same temperature as engine (up to 113°C for pressurized WEG systems)
- Resulting in junction temperatures up to 200°C
- Engine compartment temperatures up to 150° C upon start up
- Some conductively cooled applications that will operate in a 70°C ambient environment
- Air-cooled applications for battlefield power generation could required Junction temperatures > 200°C
- Requiring SiC high-frequency operation at high-temperature will push the limits of the devices as well as the packaging technology………not to mention the limits on passive components.
- Technology will need to be transition by FY17 to cut into Next-Gen vehicle designs

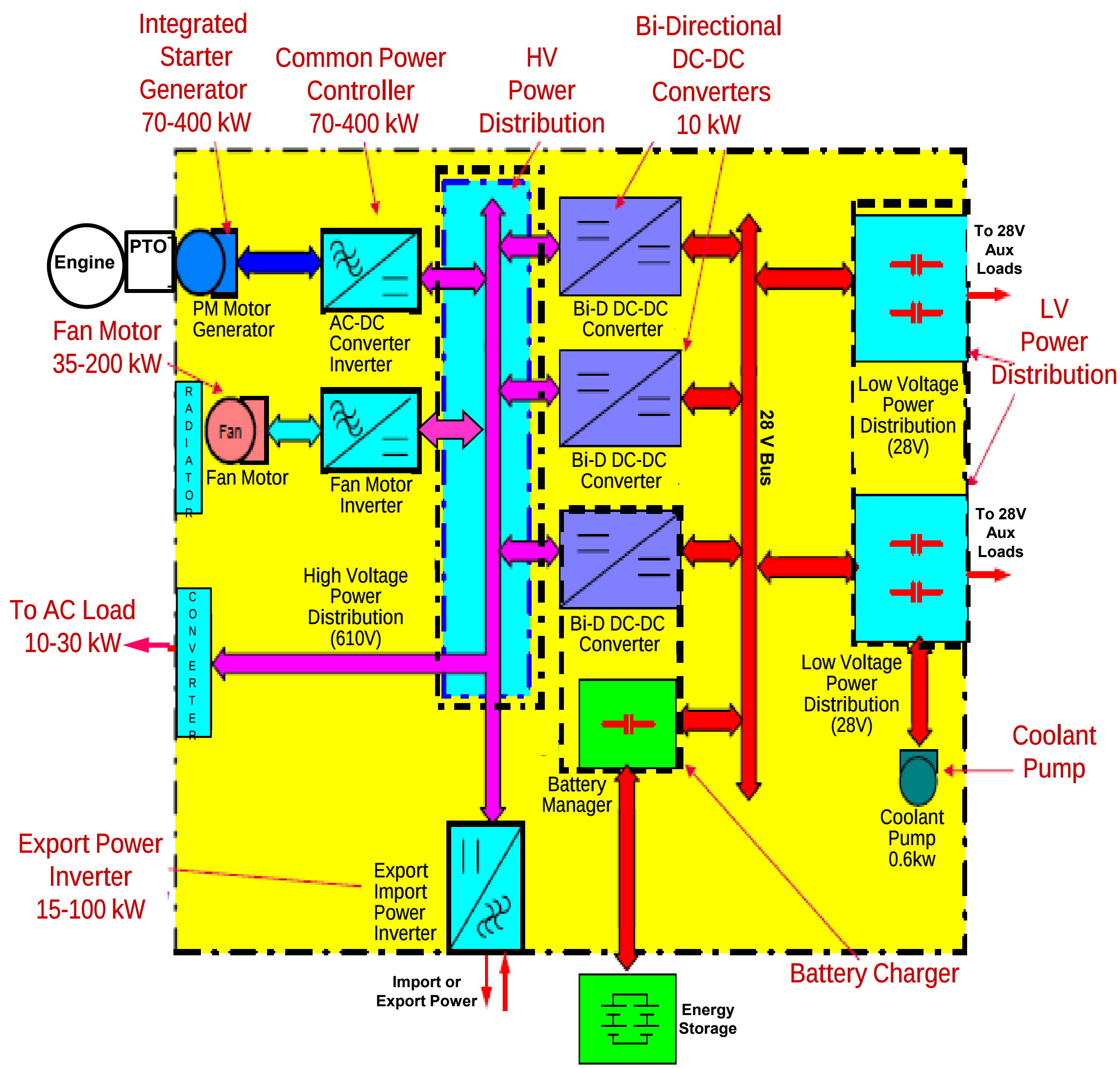
Electrical Power Architecture for Mechanical Drive Platform

Electrical Architecture Attributes:

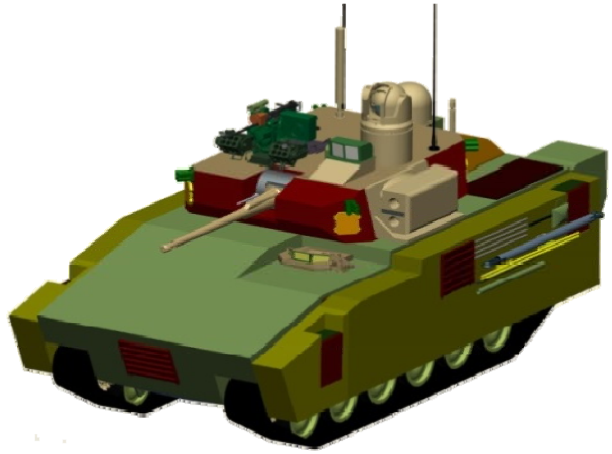
- 600 V Power generation
- 28 V Battery
- 28 V and 600 V DC busses
- 28-600 V Bi-directional DC-DC conversion
- 240 V AC Export/Import Power capability

Power: 5 – 200 kW **Current:** 30 - 700 A
Temp: 80°-150°C





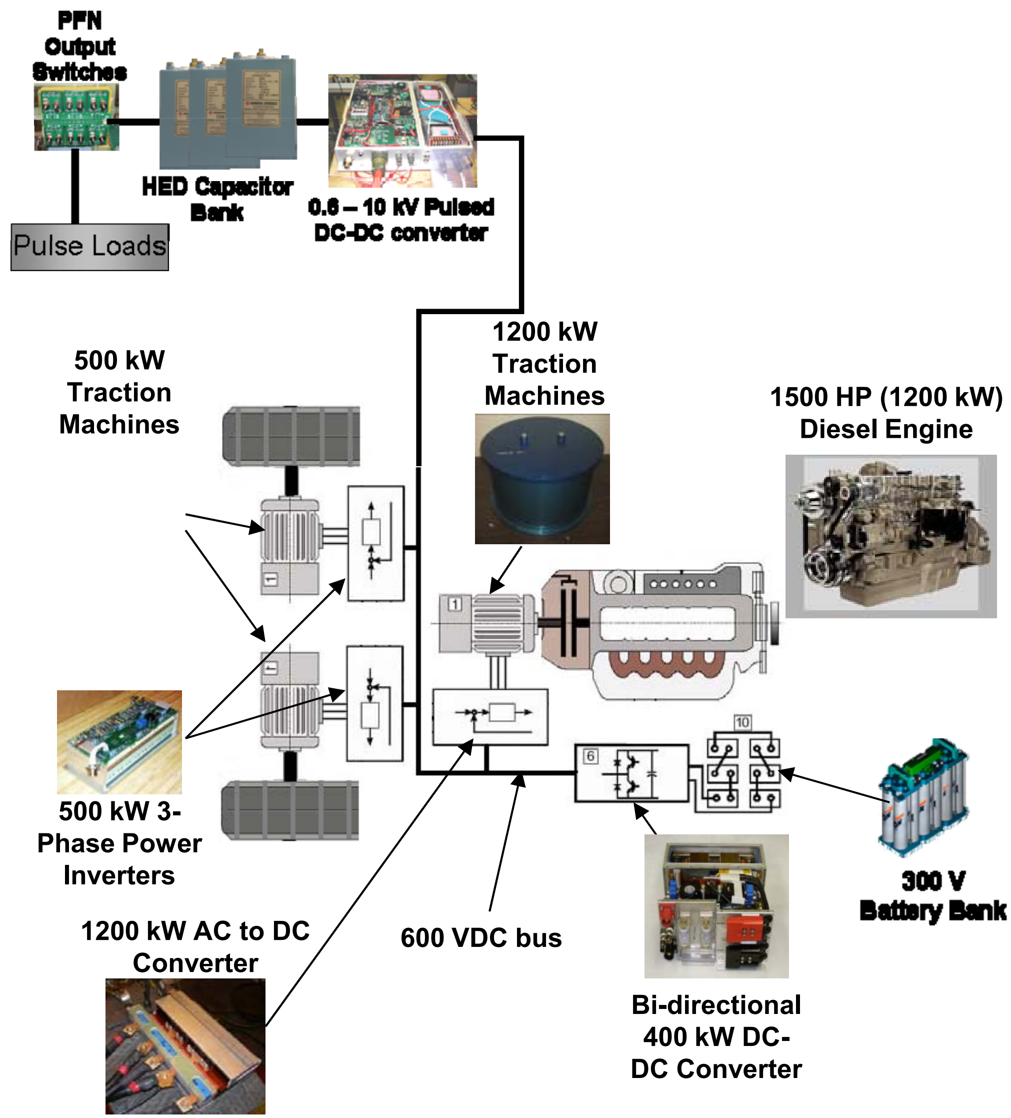
Electrical Power Architecture for Hybrid-Electric Drive Platform



Electrical Architecture Attributes:

- 600 V Power generation
- Electric Drive ✓
- 300 V Battery ✓
- 300-600 V Bi-Directional (Batt.-Bus) Converter ✓
- 600 V and 28 V Busses
- 600-28 V DC-DC conversion
- 240 V AC Export/Import Power capability

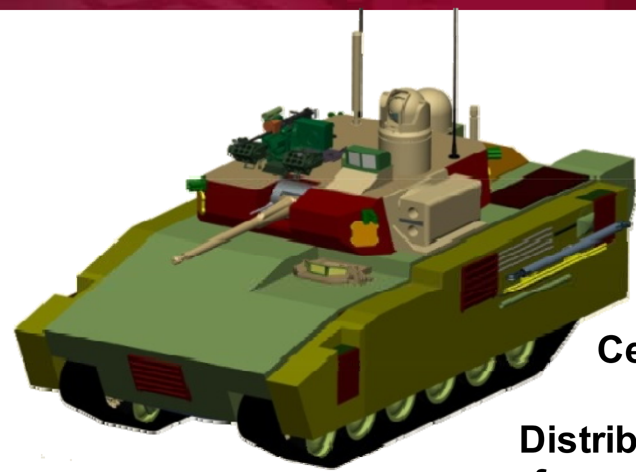
Power: 5 – 1200 kW **Current:** 30 - 2400 A
Temp: 80°-150°C



Army Platform Modernization
Pulse Power Electronic Survivability Architecture

Rationale:

- Support hybrid armor, emerging survivability/lethality
- External distribution (uncooled)
- Local high power energy store w/o engine operating

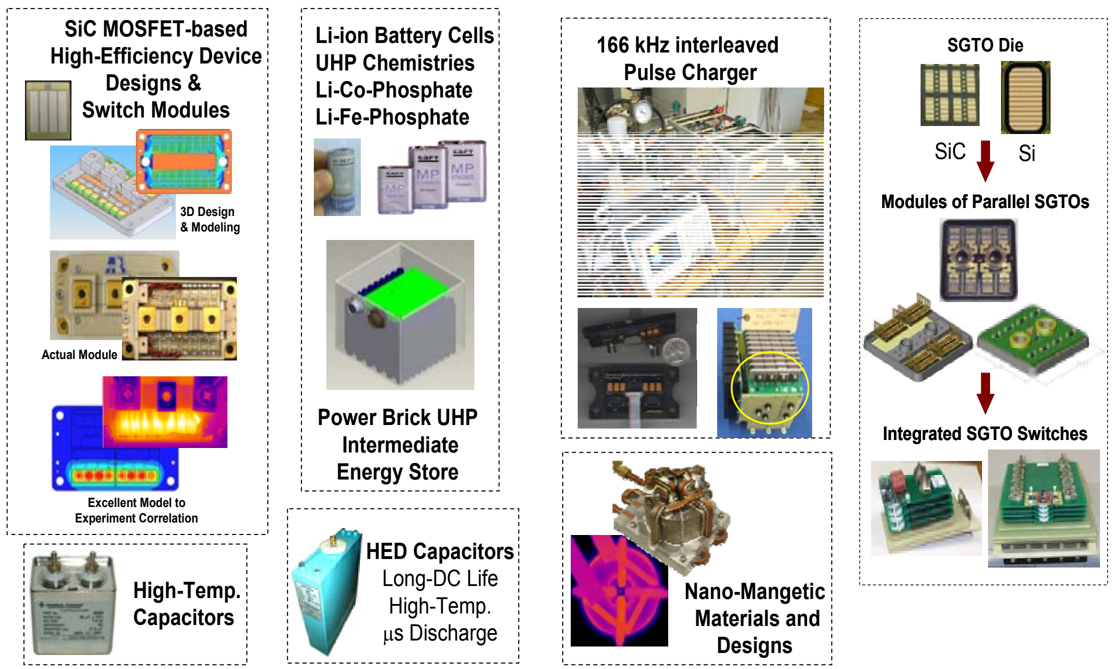


Centralized System under armor
or
Distributed Systems in multiple locations for energy distribution and redundancy

Challenges

- High temp, high freq, high current, low loss switching
- High freq/ high Bsat/ high temp advanced magnetics
- High voltage "power brick" battery
- High temp/ density storage & conversion capacitors
- Ultra-Fast Hi-voltage GW switches
- Cooling through conduction only

Voltage: 10-450 kV **Current:** 0.1-250 kA
Power: MW-GW **Temp:** 60-100°C

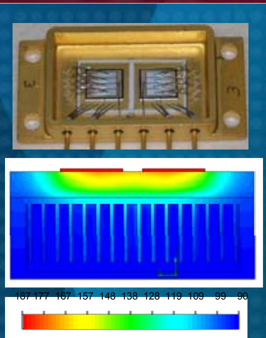


TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

High-Temperature High-Efficiency SiC MOSFET Power Modules

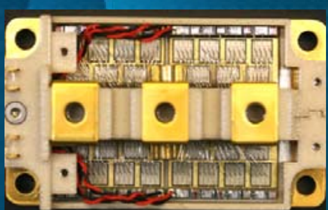
- **In 2007 Q1, PM FCS requested ongoing SiC ManTech program (FY04-09) to accelerate SiC power MOSFET & Diode development to replace Si power electronics**
  - ✓ Lack of desired top speed for MGV HE drive due to losses in Si power devices
  - ✓ Potential for single point failures of Si TDS power modules at high operating temp.
- **By end of ManTech program, SiC MOSFETs had been matured to 80 A (16X increase) and diodes matured to 100 A (10X increase)**
- **FCS TDS developmental power module populated with 900 A of SiC power devices**
  - ✓ Initial operation using both 80˚ and 100˚C coolant for 200 hours (FY10)
  - ✓ 70 % reduction in losses (at both coolant temp's) over Si TDS module at 80˚C
- **Subsequent TDS modules populated with 1,000 A of SiC power devices (FY11)**
  - ✓ 1000 hr (80°C coolant) evaluation completed maintaining same efficiency
  - ✓ 1000 hr (100°C coolant) evaluation is planned for this FY
- **Under additional funding (FY11 ARA) SiC MOSFET design matured to 100 A**
  - ✓ Subsequent power modules to be implemented and evaluated at 100˚C WEG this FY
- **PM GCV requests cont'd SiC investment to mature power devices for transition in FY17**
  - ✓ Mature high-reliability SiC ManTech processes required for 10,000-15,000 hr life time

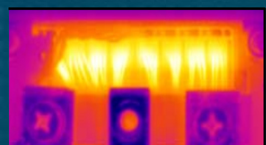
1.2 kV Silicon Carbide Power Modules Progression from 90 to 1,000 A



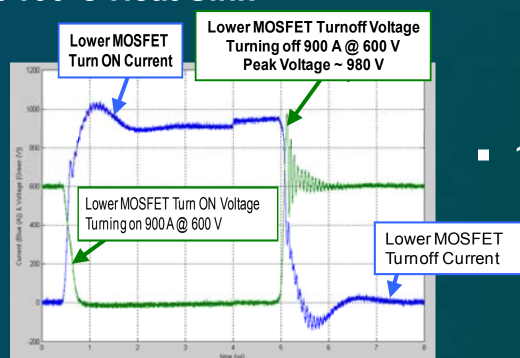
Boost converter test conditions:
- I_{RMS} = 92-A
- $T_j \approx$ 186 °C
- 90 ˚C PGW coolant
- F_{SW} = 10-kHz
- Duty = 69%
- V_{IN} = 160-V
- V_{OUT} = 491-V

Paired Large-area (0.6cm²) SiC MOSFET Die Operating at T_J = 186˚C in Boost Converter





Near-perfect SiC MOSFET Current Sharing In 1200 V / 400 A Module Operating at 100˚C Heat Sink



1200 V / 900 A Module Operating at 80˚C Heat Sink Under Stall-Zero Condition for 200 hours

❑ Demonstration of SiC MOSFETs and Diodes in High-Temperature Power Modules from FY 2008 to present

- 1200 V / 90 A power module demonstration
  - o Operated using 90°C coolant
  - o Paired 50 A Power Die operated up to 186˚C junction temperature in boost converter
- 1200 V / 400 A power module demonstration
  - o Operated using 80˚ & 100˚C coolant
  - o 50 A die show near-perfect current sharing
- 1200 V / 900 A power module demonstration
  - o Operated using 80˚C coolant for over 200 hours
  - o Under Stall-Zero condition
  - o 80 A die show near-perfect current sharing
- 1200 V / 1000 A power module currently under test
  - o 1000 hr evaluation planned for initial reliability
  - o Operating using 80˚C coolant
  - o Drive profile continuously cycled
  - o Currently at > 900 hrs of operation with no significant changes in device characteristics

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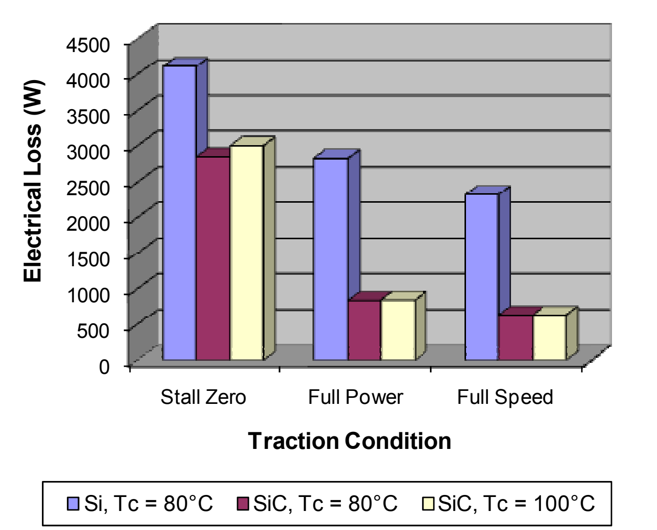
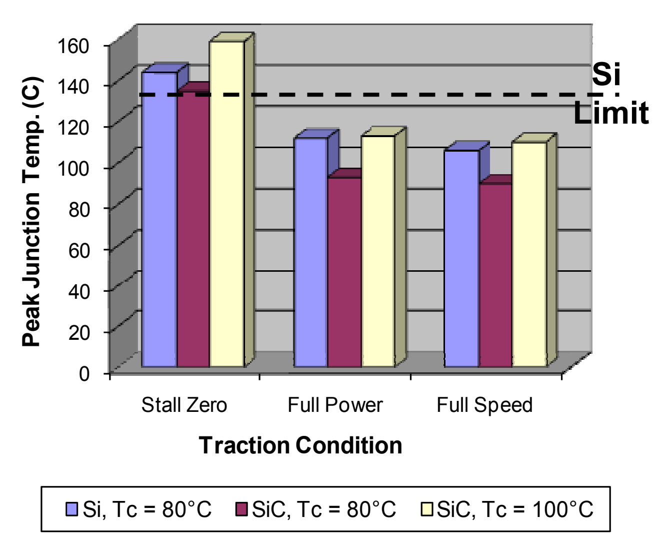
High-Temperature High-Efficiency SiC MOSFET Power Modules





Results from 200-hr Evaluation for 250 kW Traction Drive Application

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Demonstration of SiC MOSFET TDS Power Modules

- 1200 V / 900 A developmental power module demonstration
  - o Operated using 80˚C & 100°C coolant for > 200 hours
  - o Under Stall-Zero condition
  - o 25 – 40 % reduction in losses over Si for fault condition
  - o 70% reduction in losses for normal use condition over Si (estimated based on exp. Data)
- 1200 V / 1000 A fully-functional power module
  - o 1000 hr evaluation for initial reliability completed
  - o Operating using 80˚C coolant
  - o Drive profile continuously cycled (Churchville B course)
  - o No significant changes in module characteristics
  - o 70% reduction in losses for normal-use condition over Si (experimentally confirmed)
  - o 1000 hr evaluation planned at 100°C heat sink

- **Si Modules with 13.9 cm^2 IGBTs and 8.4 cm^2 diodes**
- **SiC Modules with 5.6 cm^2 MOSFETs and 3.1 cm^2 diodes**

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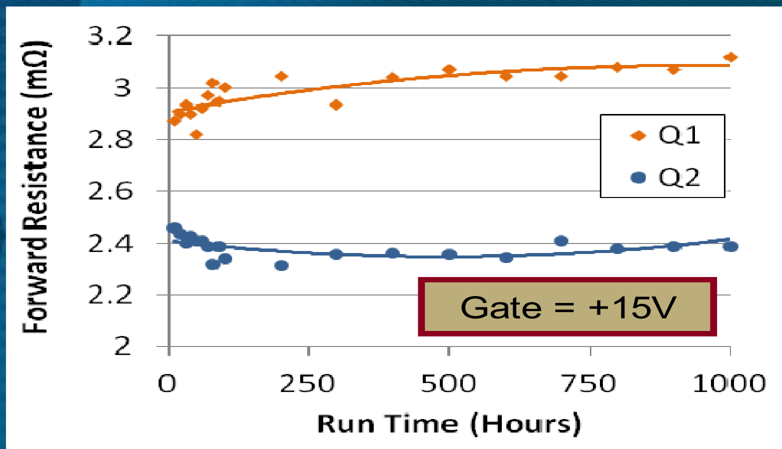
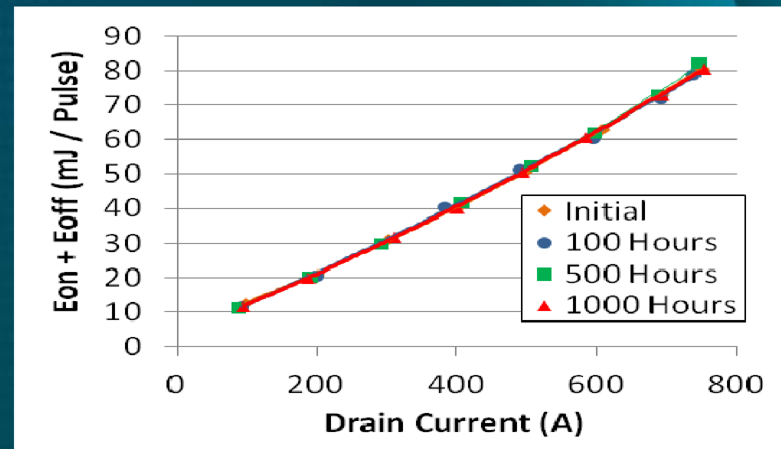
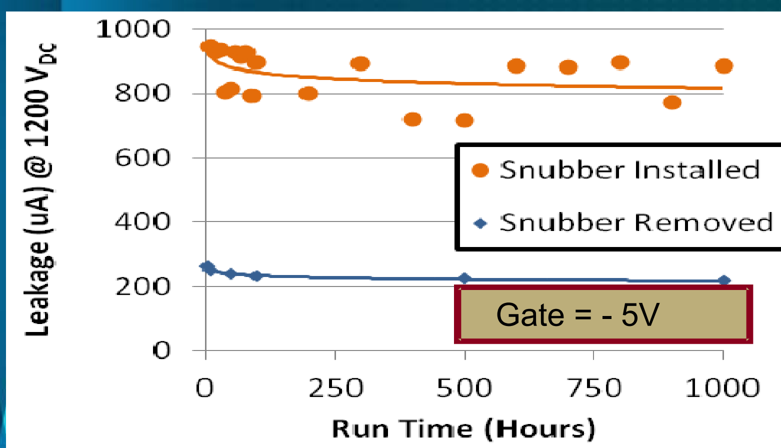
Results from1000 hr Evaluation of Fully-Functional SiC Power Module at 80°C Heat Sink



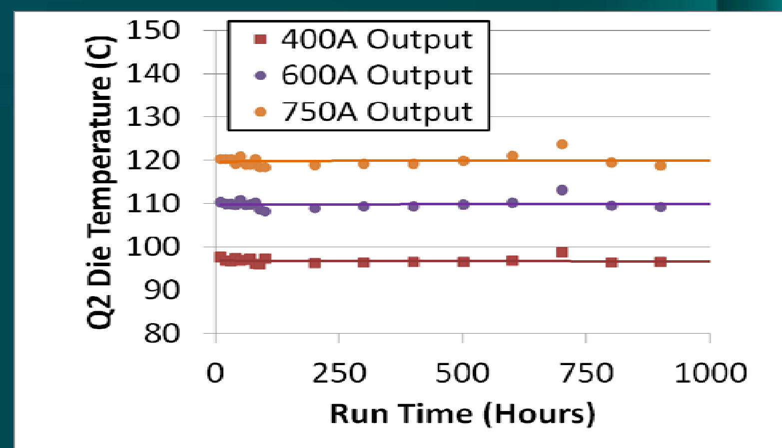
Stable Low V_f when on



No change in Total Switching Energy



Stable Low leakage when off



No change in Die Temperature

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Status & Future Plans
SiC Continuous Power Devices

❑ **GEN-1 (ManTech) 1.2 kV / 80 A SiC MOSFETs and Schottky Diodes**

✓ Capability of SiC Power Modules to operate at high temperature (80°-100°C WEG) and provide 70 % increase in efficiency over Si-based modules (200 hr evaluation)

✓ Initial reliability of SiC Power Module established at 80°C WEG for 1,000 hr under 'Churchville B' course conditions with no degradation in efficiency

✓ Same Power Module to be put under another 1000 hr test at 100°C WEG this FY

❑ **GEN-1 (ARA) : 1.2 kV / > 100 A SiC MOSFETs**

✓ Next GEN devices with same die size as GEN 1 but with increased efficiency

✓ Power module to be implemented and 1000 hour evaluation at 100°C WEG under 'Churchville B' course conditions

❑ **GEN-2: 1.2 kV / >200 A SiC MOSFETs (WEG >100°C)**

✓ Proposed and current programs to increase power rating and mature technology to MRL8,TRL7 (at enhanced reliability and reduced cost) by FY16

✓ Current programs will mature to only MRL6/7, TRL6; and at increased cost

✓ Proposed programs need to be fully funded to insure transition in FY16/17

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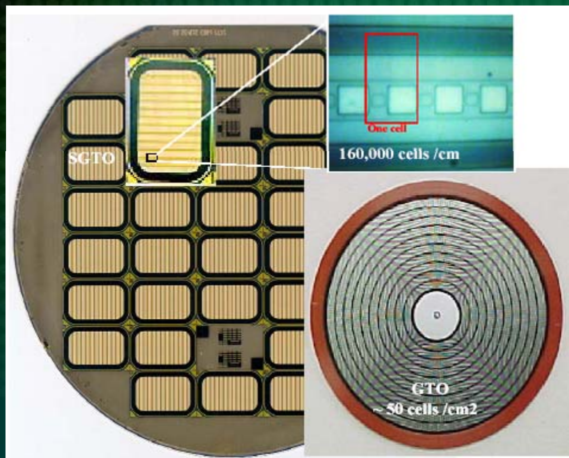
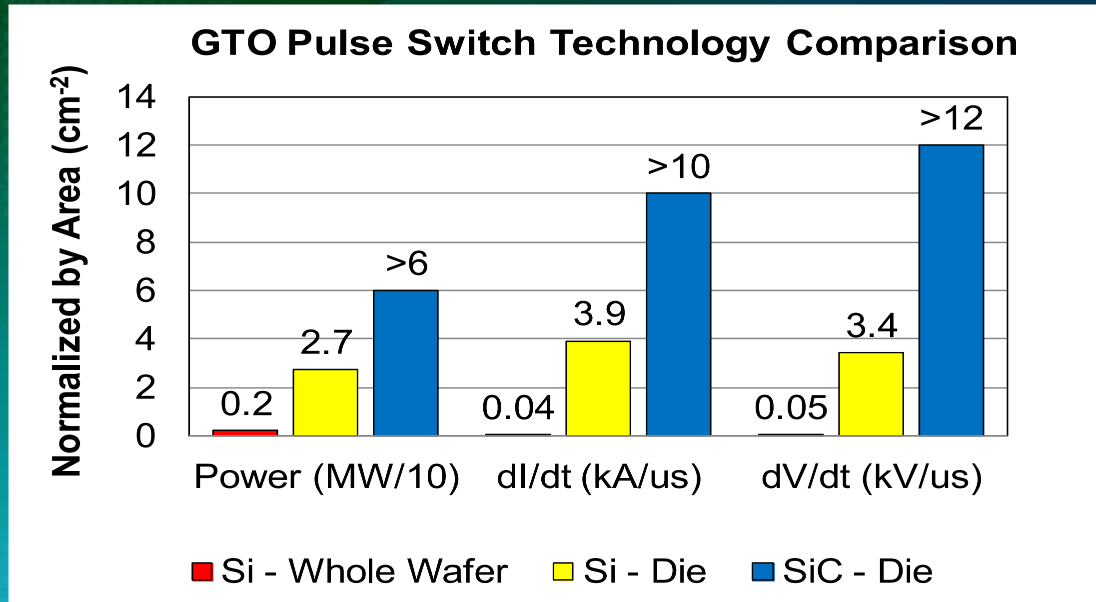
Pulse Switch Technology Comparison

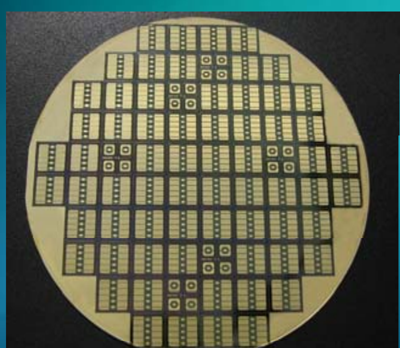
Si Whole Wafer GTO vs. Si SGTO Die



Basic Die (3.5 cm^2) 20 kA, 6 kV
14 kA/µs, Turn-on Gain = 10^6

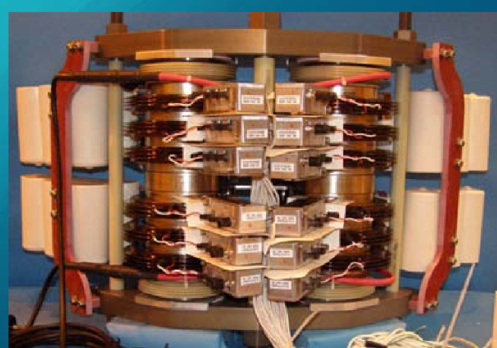


SiC SGTO Die on 4" Diam. Wafer



Basic Die (1.0 cm^2) 5 kA, 12 kV
10 kA/µs, Turn-on Gain = 10^6

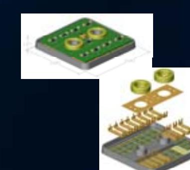
Packaged Pulse Power Switch Assembly (400 kA)



Si 8 kV Clamped Whole Wafer
With Snubber Caps

Si 16 kV Die-Based
No clamps, No Snubbbers

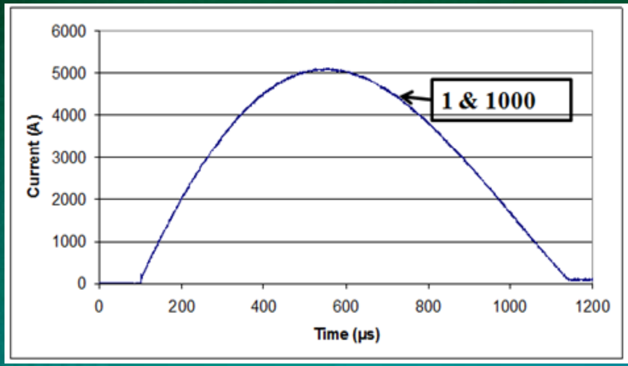
Building Block Module



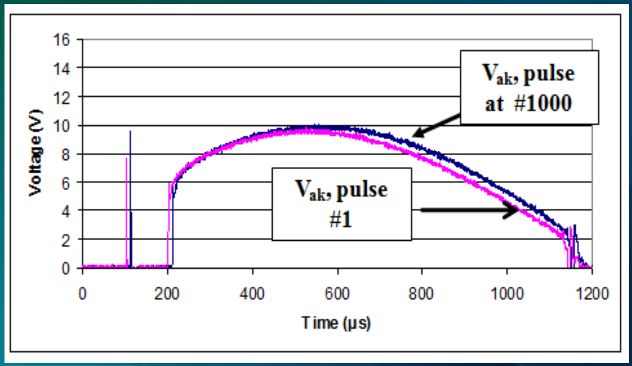
8-Die Module
for Si or SiC

Results of Small-Scale Module (2.4 cm2 die area) 1000-Pulse tests at Wide and Narrow Pulse Width

Wide-Pulse Performance

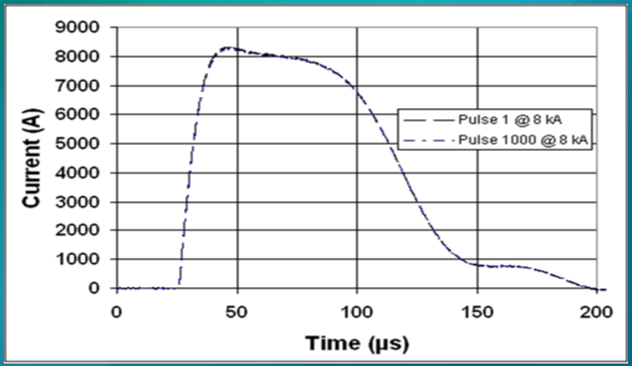


SiC SGTO module peak current. Overlay of pulse 1 and 1000.

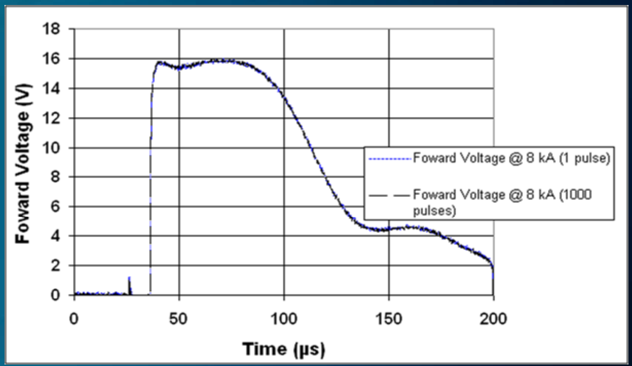


SiC SGTO module forward voltage drop. Overlay of pulse 1 and 1000.

Narrow-Pulse Performance



SiC SGTO module peak current . Overlay of pulse 1 and 1000.



SiC SGTO module forward voltage drop Overlay of pulse 1 and 1000.

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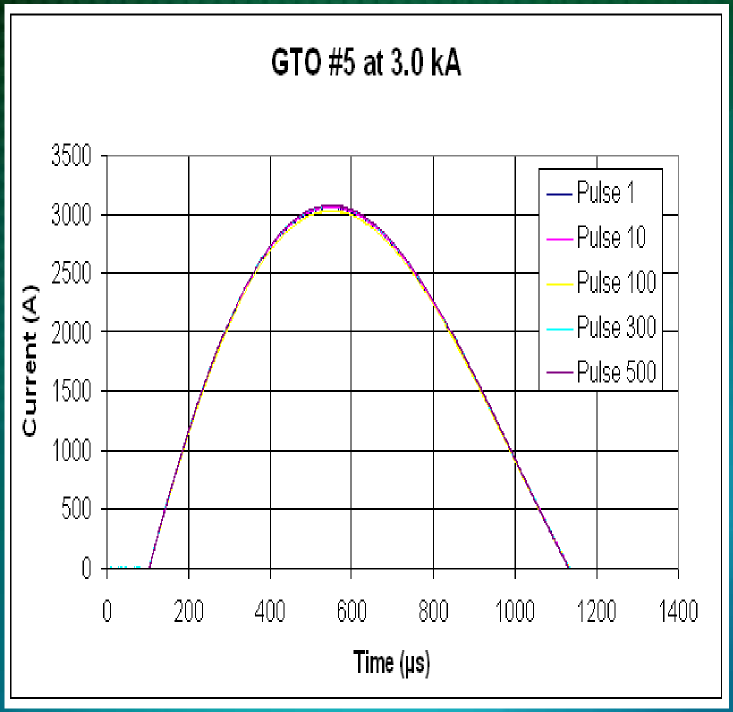
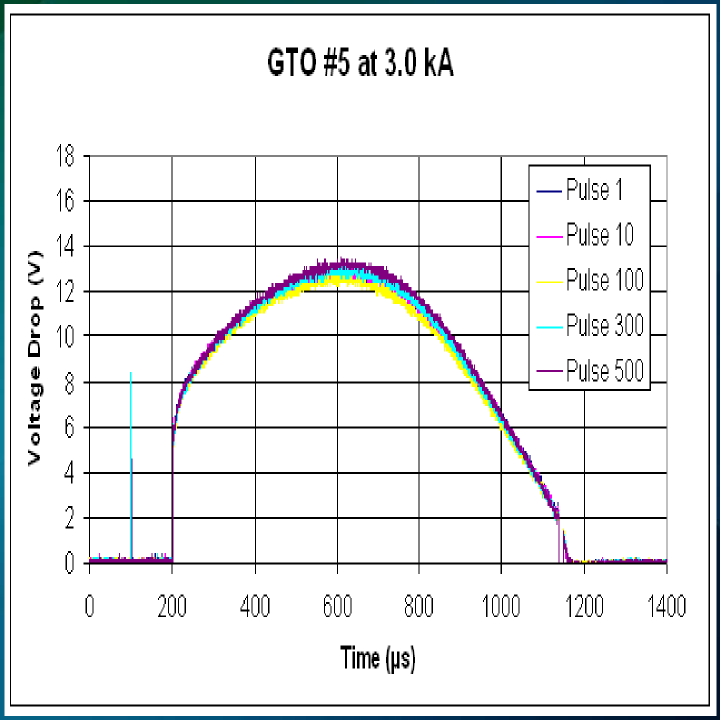
Initial Results for Wide Pulse Evaluation 1 cm2 SiC GTOs





- ✓ **50 % Increase in Current Density over previous Gen Switch (0.6 cm^2)**
- ✓ **Data has been taken (but not available) to show 1 cm2 die provides 5 kA at narrow pulse width application**

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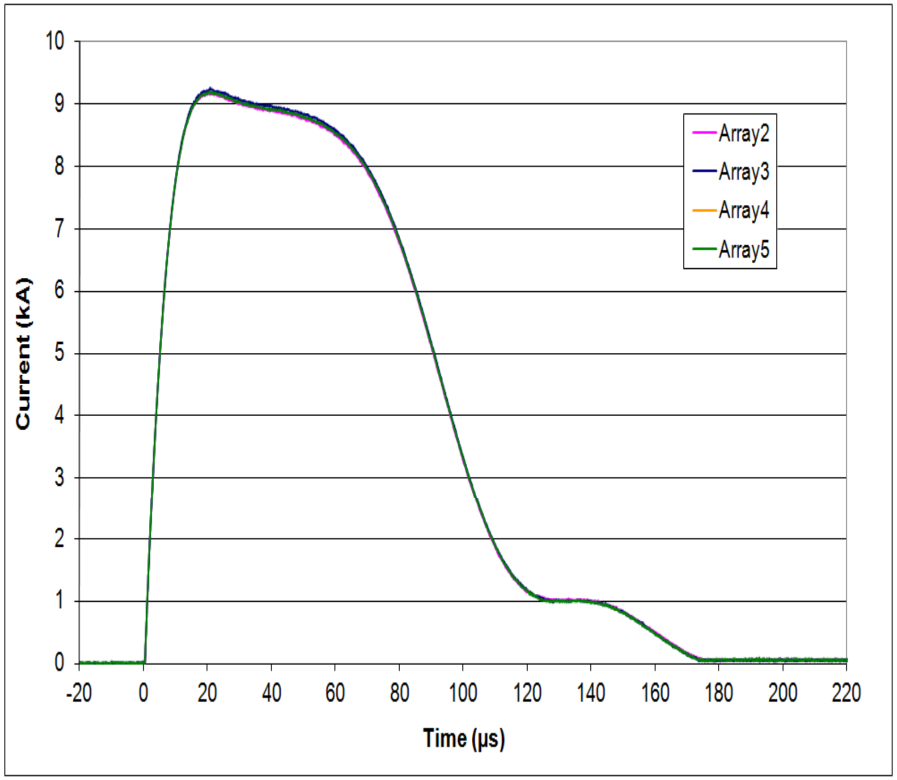
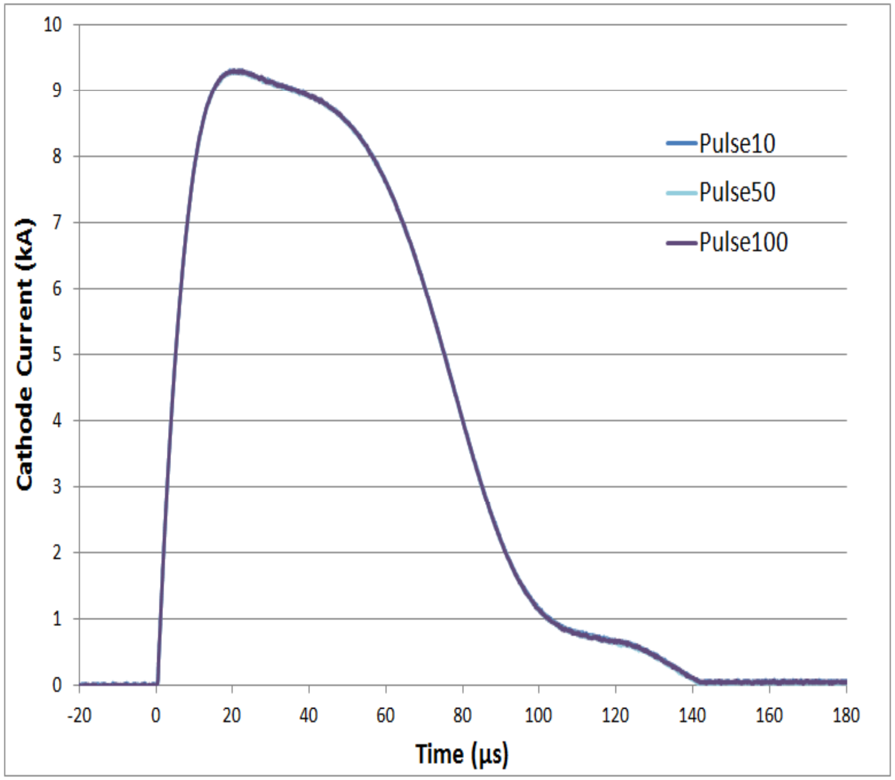
Initial Results for Narrow Pulse Evaluation SiC SGTO 1 x 2 Arrays (1cm² die)



Four SGTO arrays (2 cm² die area)
each switched at 9 kA



Array #3 (2 cm² die area)
Initially switched at 9 kA for 100 pulses

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Status and Future Plans for Si and SiC Pulse Switches

- **Si SGTO Since 2004:**
  - ✓ Baseline Die size (3.5 cm^2) has remained the same
  - ✓ Increased Peak current (from 10 to 16 kA) and Blocking Voltage (from 4 to 6.5 kV)
  - ✓ Developed 'Stitch' Die at increased die size (2 X) and Current (2.5 X)
- **Si SGTO Future Work as Near-term solution**
  - ✓ Optimize packaging to handle increased current and voltage for baseline die
  - ✓ Continue with Stitch Die to optimize current density and voltage (6.5 kV)
  - ✓ Optimize standard module package for 'Stitch' device's increase current density

- **SiC SGTO Since 2004:**
  - ✓ Increased Die size (from 0.16 to 1 cm2)
  - ✓ Increased Peak current (from 0.8 to 5 kA) and Blocking Voltage (from 2 to 12 kV)
- **SiC SGTO Future Work as Mid- to Far-term solution**
  - ✓ Increase die size up to 2 cm^2
  - ✓ Increase peak current to 15 kA and Blocking Voltage to 15-20 kV
  - ✓ Optimize Si standard module package for SiC increased current and voltage

- **Current program will mature to only MRL6, TRL6 and at increased cost**
- **Proposed programs need to be fully funded to insure transition in FY16/17**

SiC Power Switch Summary

- **Continuous Power Applications**
  - ✓ SiC TDS module operating at 80° and 100°C WEG with 70% greater efficiency than Si TDS module; and at 40% replacement.
  - ✓ Proposed and current programs to mature MOSFET to 300 A @ > 100°C WEG
- **Pulse Power Applications**
  - ✓ Si SGTO die pulse switch operating at 10X power density of Si whole-wafer switch
  - ✓ SiC SGTO die operating at 2 X greater power density than Si SGTO die
  - ✓ Proposed and current programs to mature SiC switch power density by another 2-3X at increased efficiency.
- **Above component work can reduce power system size by up to 2X for continuous and 4X for pulse power applications with efficiencies at >2X vs. Si-based systems**
- **Proposed programs need to be fully funded to insure transition in FY16/17**
  - ✓ Current programs will mature to only MRL6, TRL6 and at increased cost