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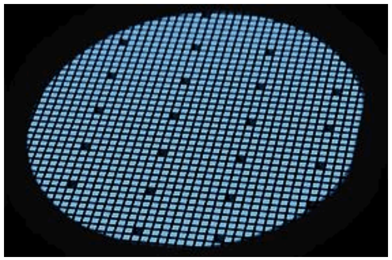

# 6.5KV SILICON CARBIDE JFET SWITCH MODULE FOR HIGH DENSITY POWER CONVERSION SYSTEMS


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EESAT TECHNICAL CONFERENCE

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PORTLAND, OREGON

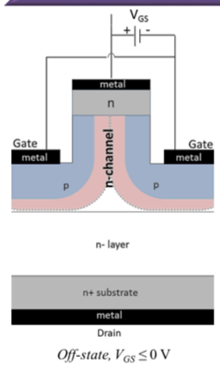
# Contents

- Project Overview
- Motivation
  - Why SiC 6.5 kV JFETs?
- 6.5 kV Applications
- 6.5 kV Enhancement Mode JFET
- Power Module Overview
- Buck Converter Testing
- Summary

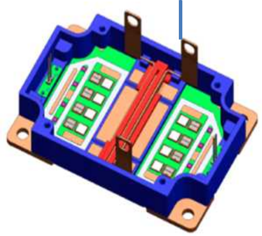
# Project Overview

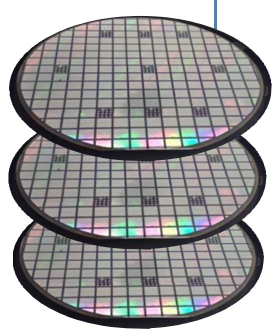
| 2012 | | 2013 | 2013 | | 2014 | | | | 2015 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Q3 | Q4 | Q1 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 |
| Phase I | | | Phase II | | | | | | | |

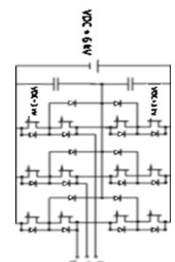
Device Design → Epitaxial Growth Development → Module Design → 6.5 kV Device Fabrication → Application Study → Module Assembly → Converter Testing

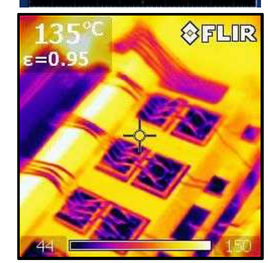













*"Molecules to Megawatts"*

# Why 6.5kV SiC JFETs?

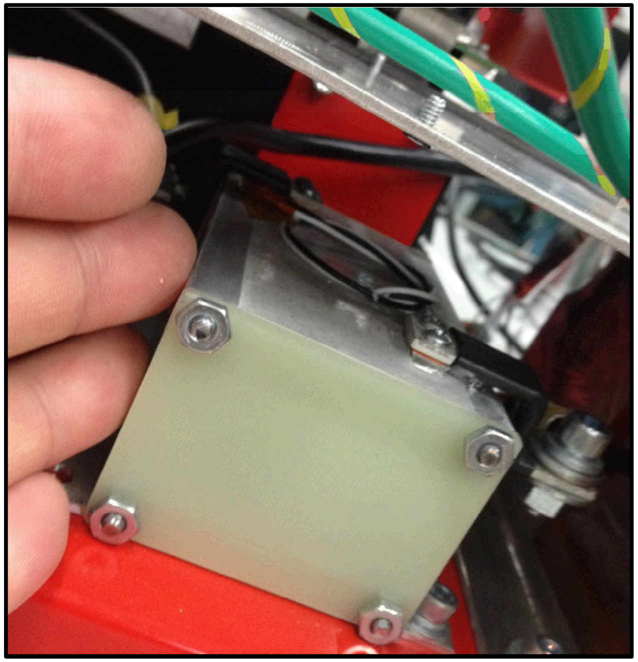
| | Norm Off SiC JFET | Si IGBT | SiC MOSFET | SiC Bipolar (IGBT, GTO) |
|---|---|---|---|---|
| Voltage, kV | ~1 - 10kV | ≤ 6.5 kV | ~1 - 10kV | ~1 – 20 kV |
| Switching Losses | 1X | 20X | 1X | 3X |
| Device Type | Unipolar | Bipolar | Unipolar | Bipolar |
| Max Temperature | 200°C | 175°C | 150°C | 150-200°C |
| Reliability | Robust | Robust | SiC-Oxide Issue | $V_F$ Drift from BPD issue |

SiC JFETs can address 6.5kV applications, but with 20X lower losses than 6.5kV Si-IGBTs

- Low Losses Enable High Frequency Switching
- Enables Higher System Power Density

$$\frac{Power}{Volume} \approx frequency$$

# Example: Inductors



**6 kHz**
~800uH, 60 Amps, 20 lbs

**20 kHz**
~200uH, 55 Amps, 3 lbs

Vol = 6480 $cm^3$ → Vol = 396 $cm^3$

16X Volume Reduction!

USCi
United Silicon Carbide, inc.

# Example: 30kW SiC Inverter

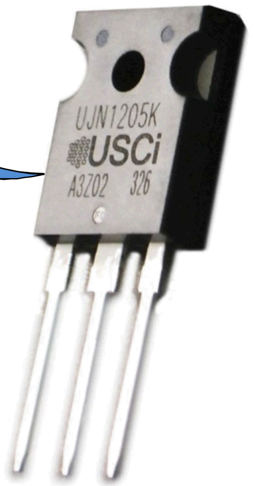
PRINCETON POWER SYSTEMS
Clean Power Made Simple™

30kW Bidirectional Inverters

1200V Si-IGBT
**6kHz**
Floor Mount


1200V SiC-JFET
**20kHz**
Wall Mount

- Power Density Increase by >3X due to faster switching – From 6kHz to 20kHz
- Peak Efficiency Increase of ~ 2%
- Power stage uses USCi 1200V SiC-JFET



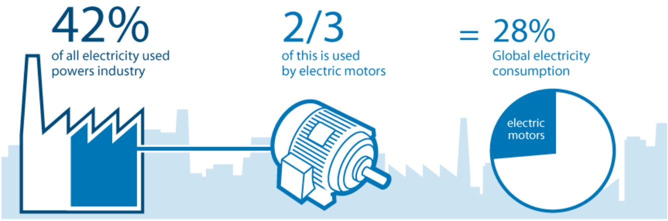

UJN1208K TO-247

| Parameter | Value | Unit |
|---|---|---|
| $R_{DS(on)}$ | 80 | mΩ |
| $V_{DS}$ | 1200 | V |
| $T_{max}$ | 175 | °C |

# 6.5kV SiC JFET Module

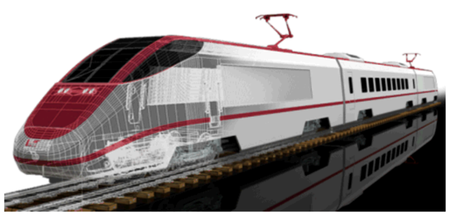
USCi United Silicon Carbide, inc.

- The 6.5kV JFET module targets higher power (MW) applications where systems can benefit from higher DC-Link voltages and faster switching frequencies:




## Applications

- Variable Speed Industrial Motor Drives
- HV Battery Stacking
- Transformerless Grid-Tie
- Heavy Vehicle Traction Converters
- Hybridization of Ships
- Flywheel: High Voltage Stators



Trains

GVEA BESS 5kV DC-Link (Alaska)

USCi United Silicon Carbide, inc.

# Contents

# 6.5 kV Enhancement Mode (Normally-Off) JFETs

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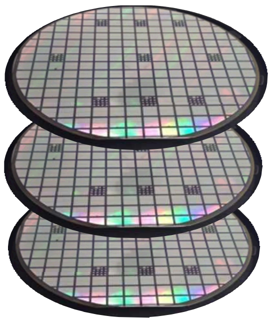
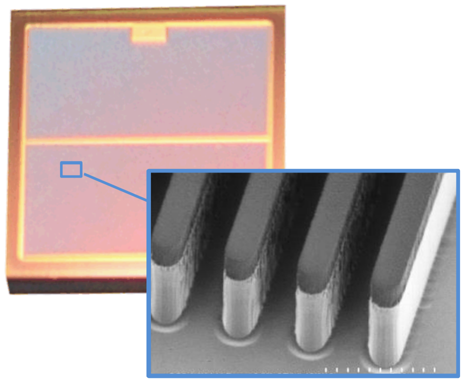
100mm Wafers



6 X 6 mm

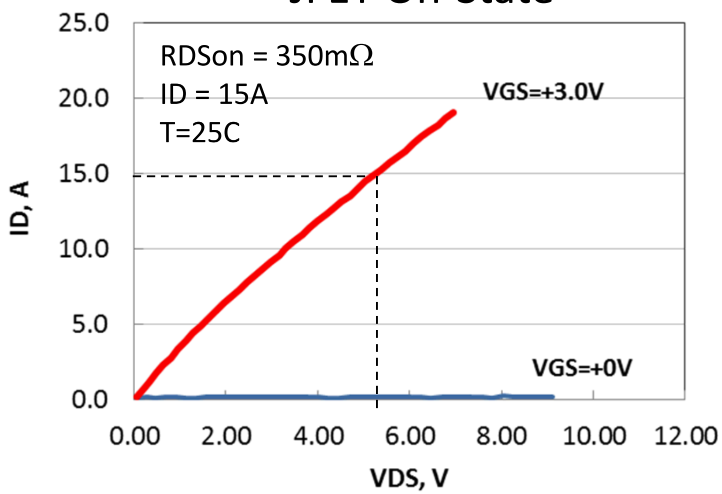


JFET Source Mesa

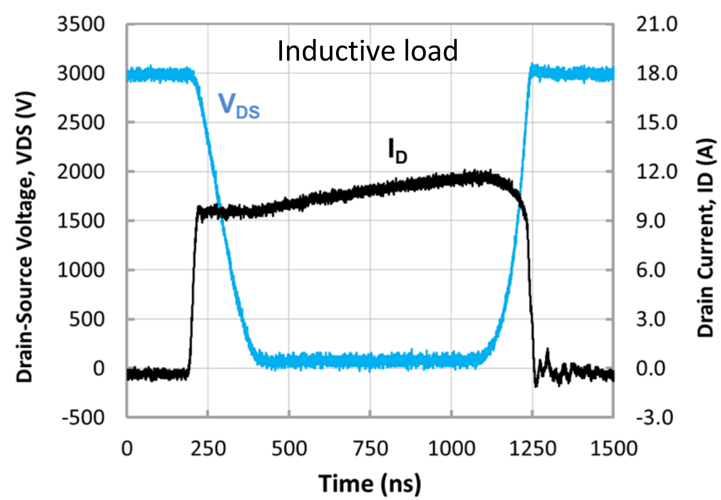
| Parameter | Design Target | Meas. |
|---|---|---|
| Rise Time, $t_r$ | 150 ns | 149 ns |
| Fall Time, $t_f$ | 100 ns | 99 ns |
| Turn-on $E_{on}$ | 2.66 mJ | 2.71 mJ |
| Turn-off $E_{off}$ | 0.9 mJ | 1.54 mJ |

Ultra Low Switching Losses

JFET On-State

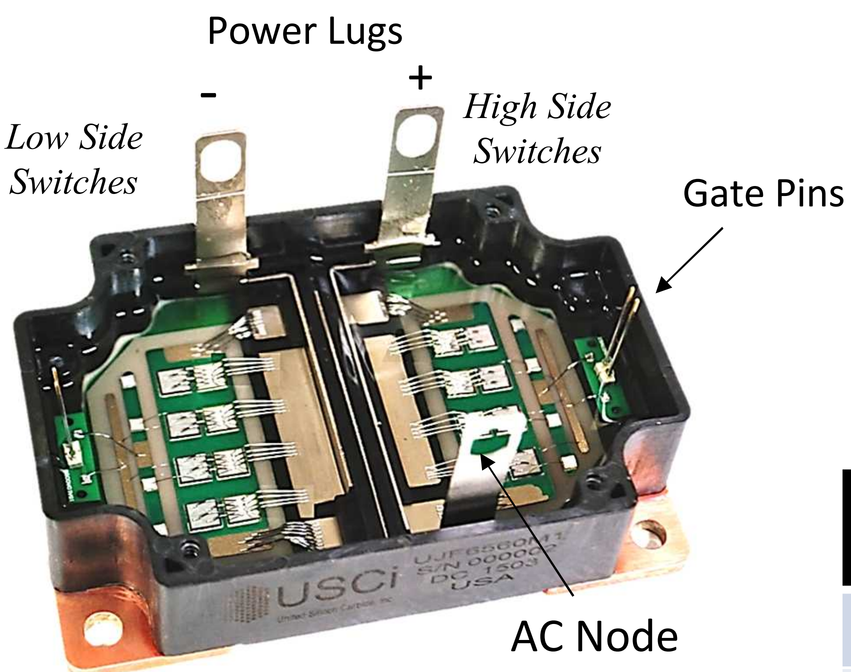


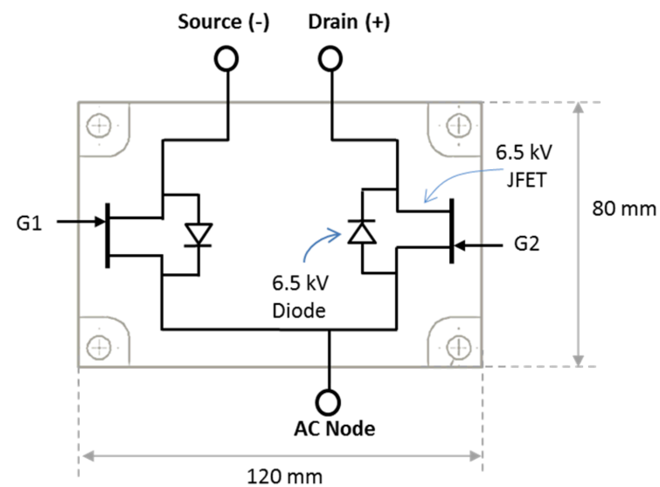

3kV -11A Device Switching



# 6.5 kV Half-Bridge Module

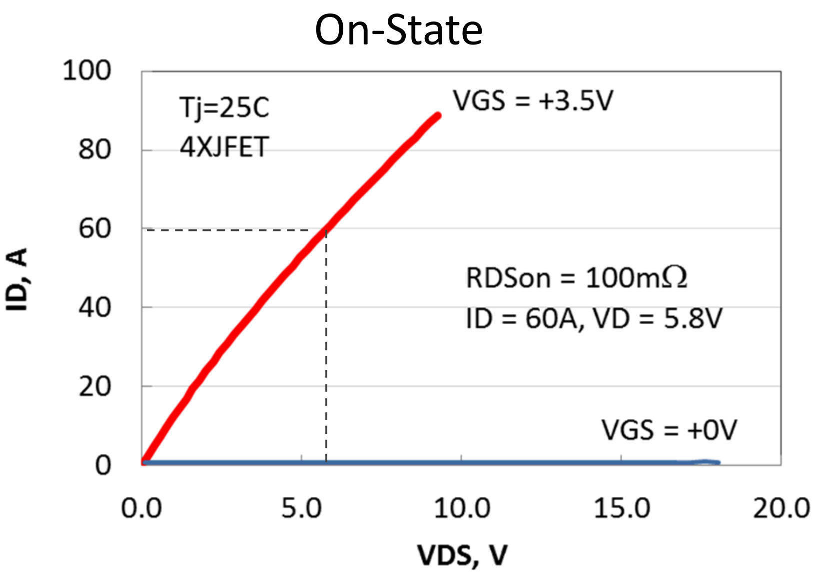
- 4 JFETs in parallel with 4 Diodes in antiparallel
  - Each switch set rated at 60A (4x15A)

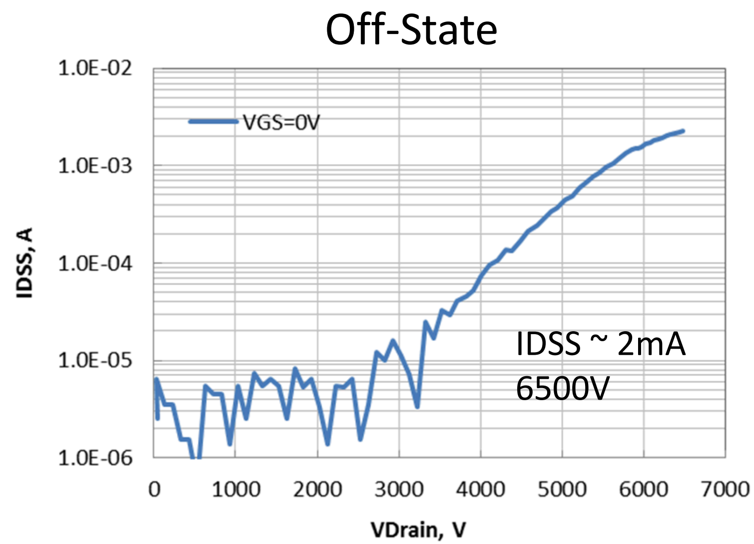


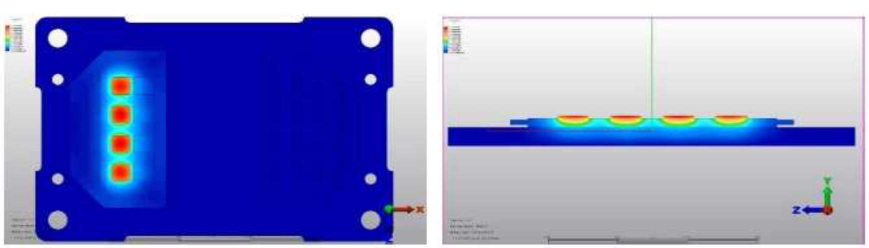

| Module Rating | | Typical Operation |
|---|---|---|
| Off-State | VDS = 6500V | VDS ~3300V |
| On-State | $ID_{(Cont,T=25C)}$= 60A | $ID_{(RMS, Max)}$ ~ 40A |

# Module Performance




0.107 °C/W

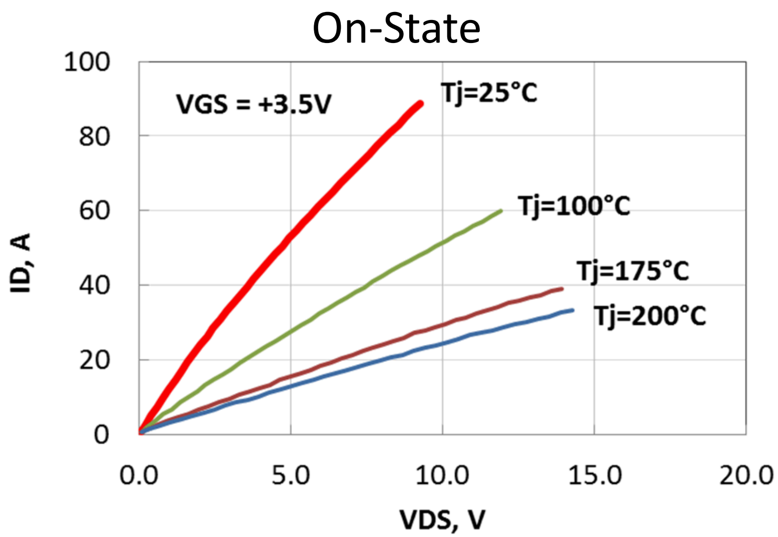


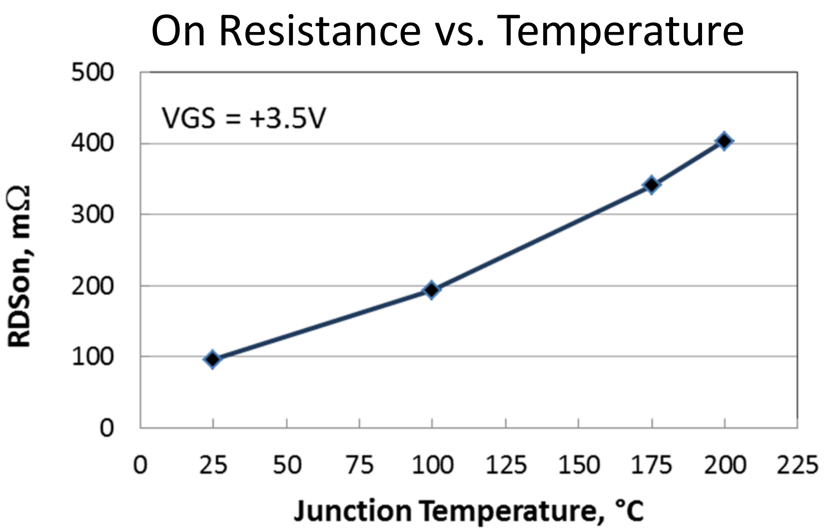
Optimized Chip Spacing

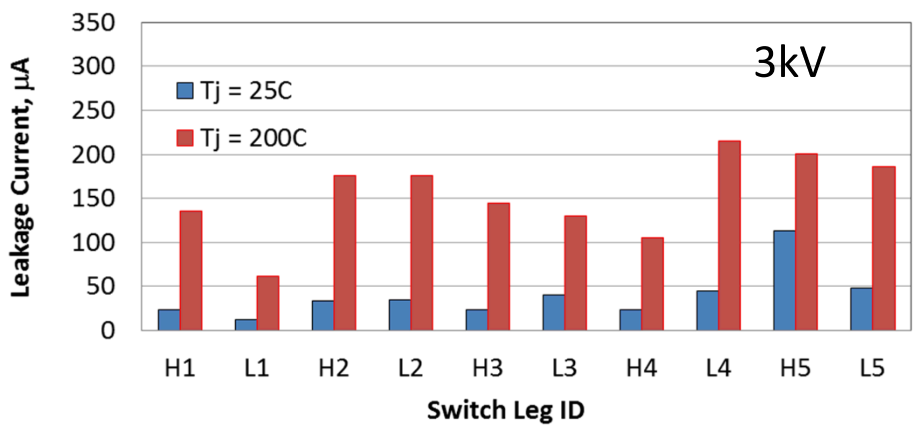
| Thermal Resistance | Value (C/W) |
|---|---|
| $R_{TH\text{-}JC}$ (Junction-Case) | 0.11 |
| $R_{TH\text{-}HS}$ (Heatsink-Amb) | 0.09 |
| $R_{TH\text{-}Tot}$ (Junction-Amb)* | 0.20 |
| Max Power Dissipation | 875W/per leg |

*measured

# High Temp Performance



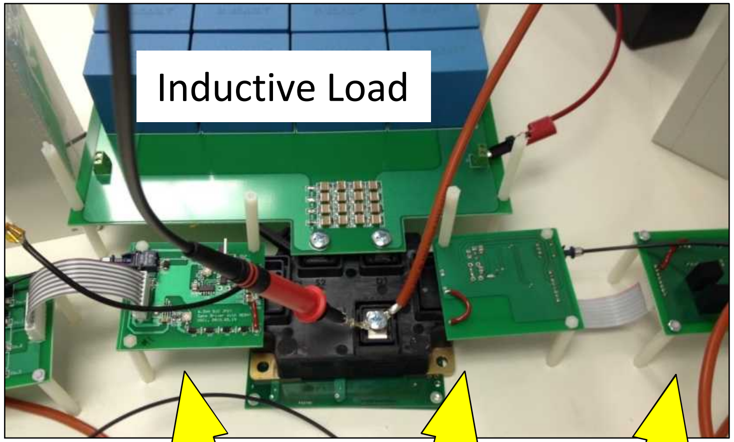




- Stronger Positive Temp Coefficient than expected
  - RDSon 4X increase at 200°C
  - Should be 3X
- Leakage < 250uA at 3kV for Tj=200°C

# Module Switching

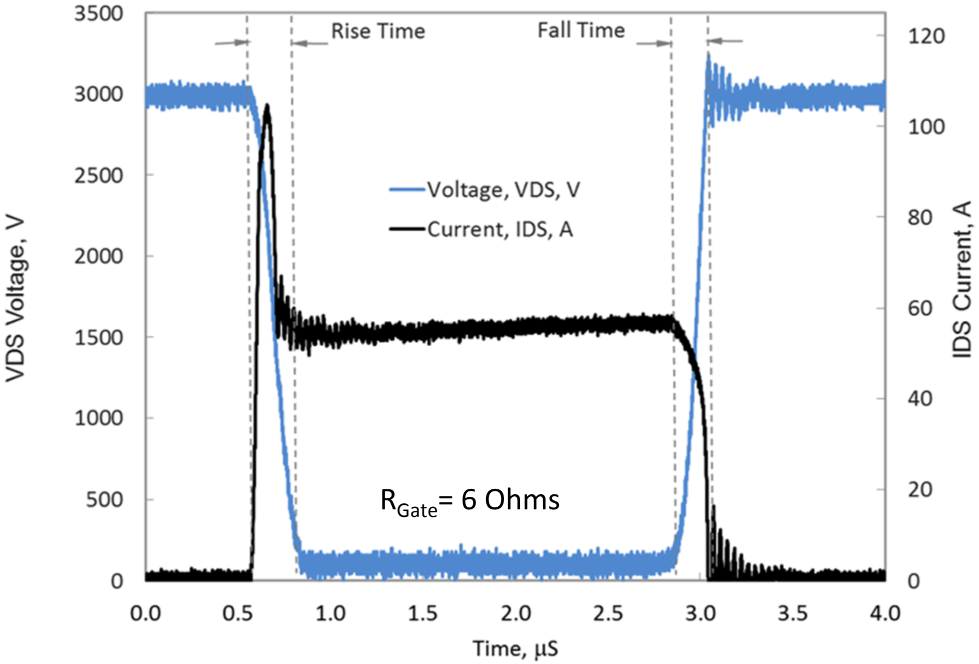
- USCi Designed Gate Drivers
  - 2 Level Design:
    - +12V Turn-on
    - +5V On-state




Switch Driver IC's

TTL Logic IC's

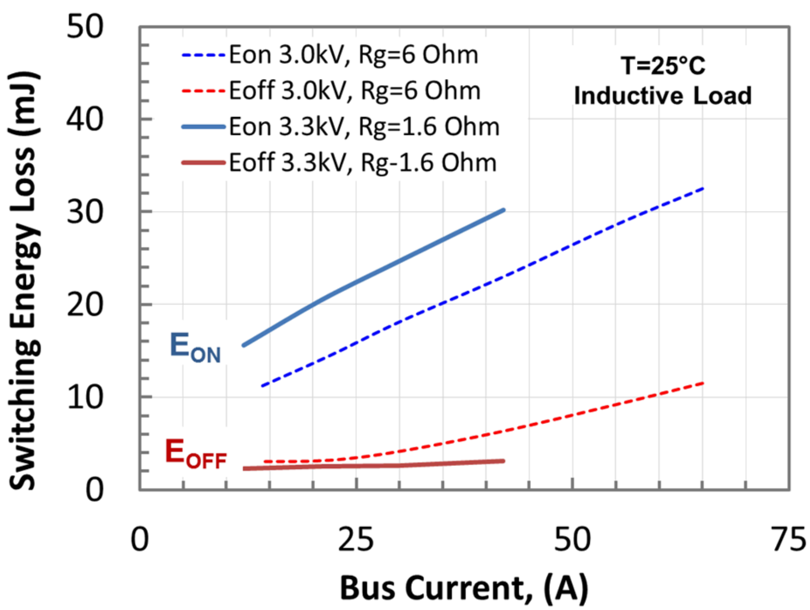
3kV – 60A Module Switching Waveform



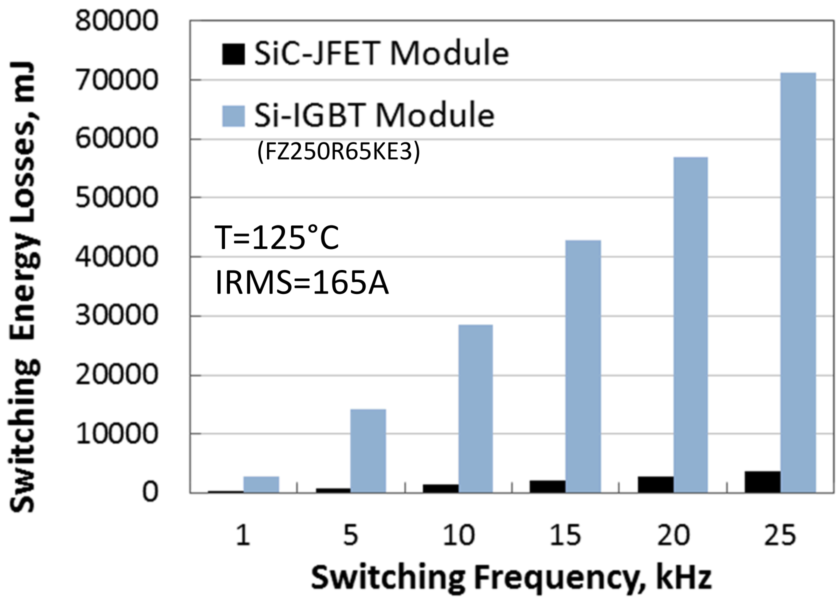

- Rise Time = 185ns, $E_{on}$ = 28 mJ
- Fall Time = 130ns, $E_{off}$ = 9.2 mJ

# Module Losses

- Measured Turn-on and Turn-off Energies vs. bus current and gate resistors, $R_g$



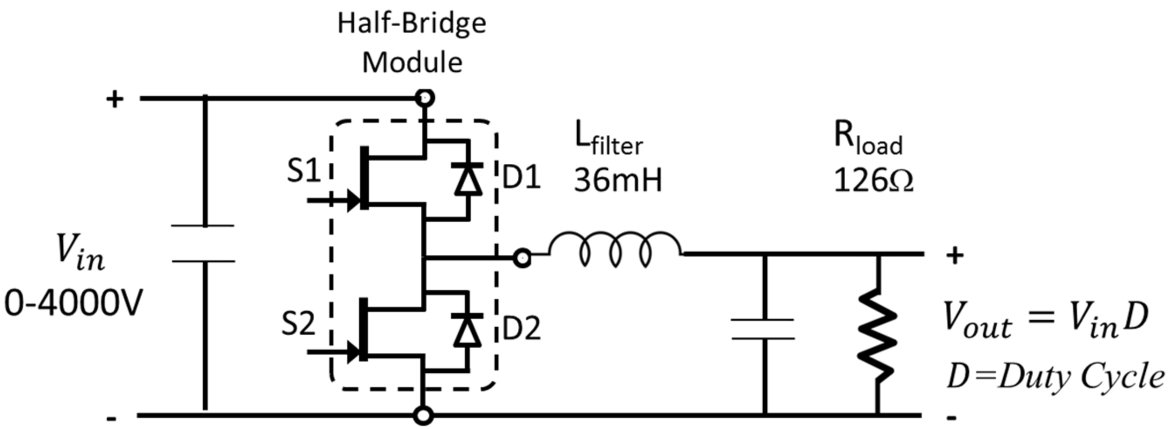

- Compare to 6.5kV 250A Si-IGBT
- 4 SiC Modules in Parallel to scale to 240A max rating



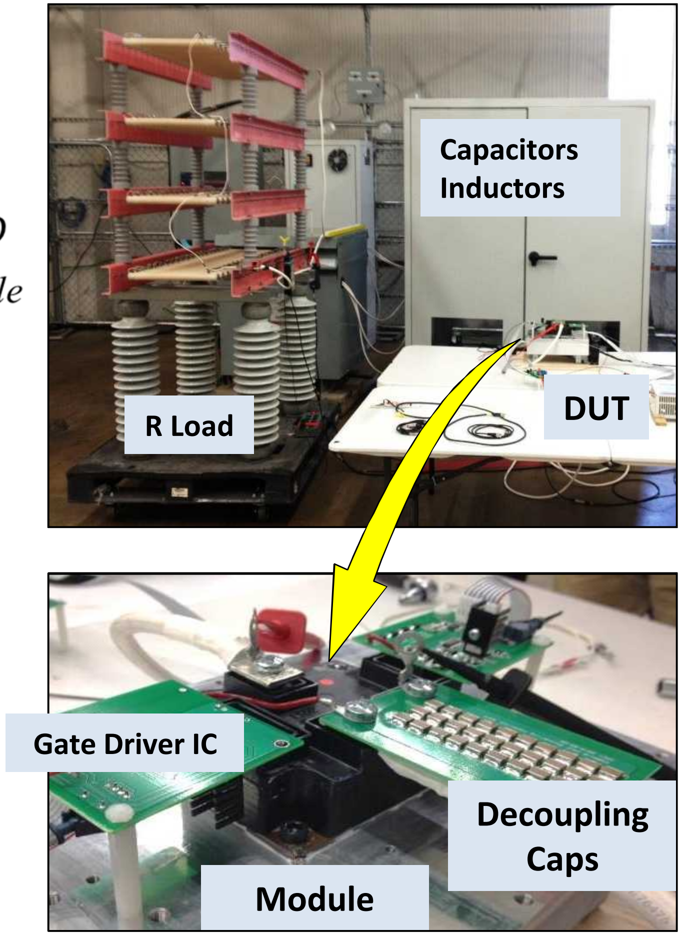

20X reduction in switching losses!

# Contents

# Buck Converter Testing

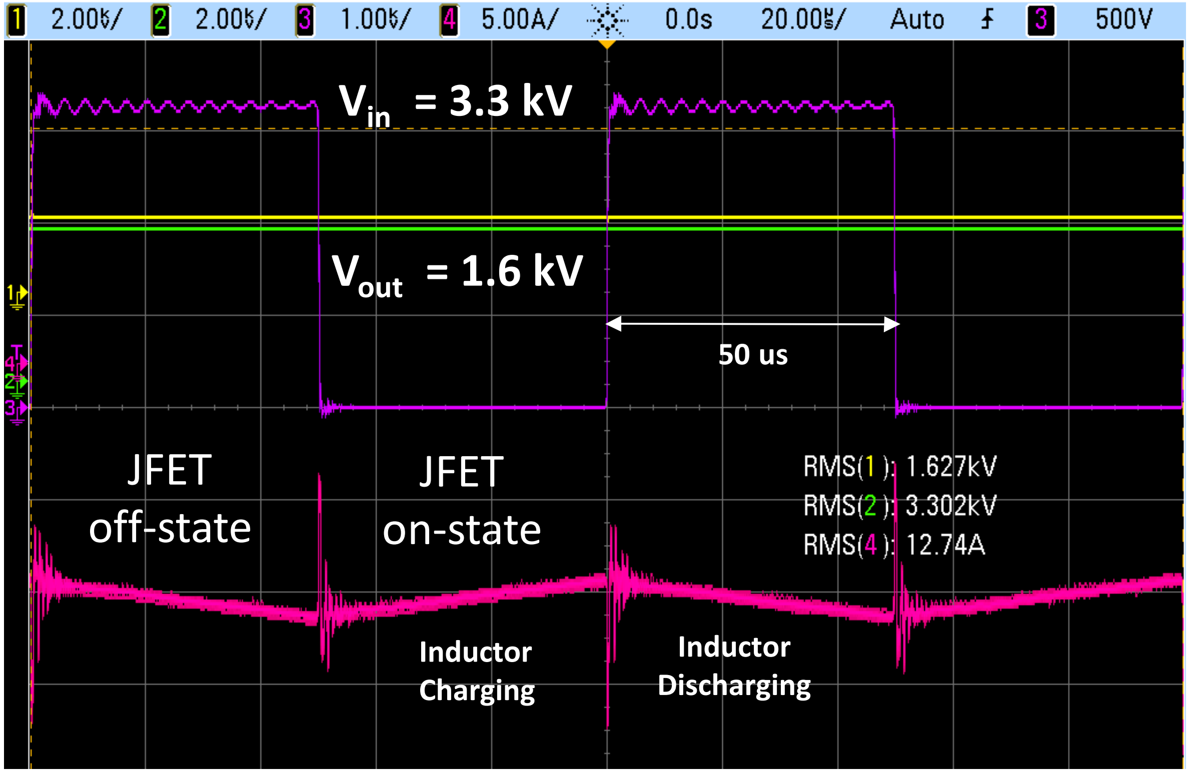


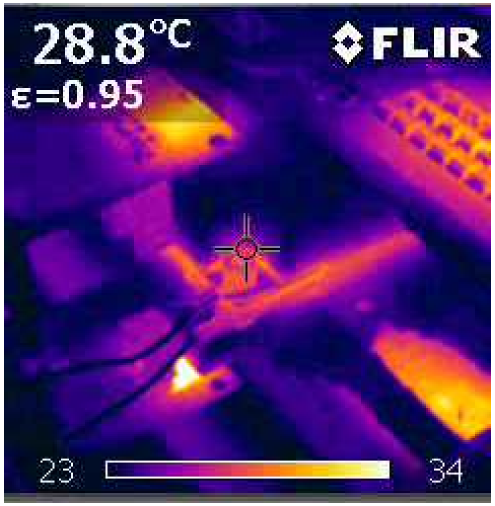

- DC/DC Down Converter
- **S1 On-State**
  - Current passes through switch, S1
- **S1 Off-State**
  - Current passes through diode, D2
- Steady-State Operation
  - Measure Module Temperature & Losses



# Buck Converter Operation

- Example: Continuous Mode Operation
- 50% Duty Cycle - Hard Switching
- 10 kHz Switching Frequency, $P_{out}$ = 21kW



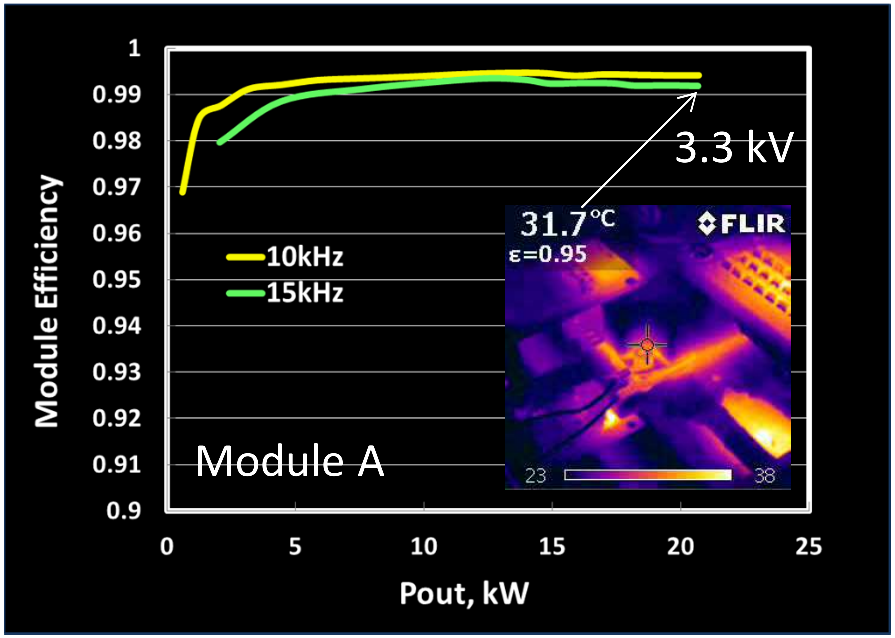



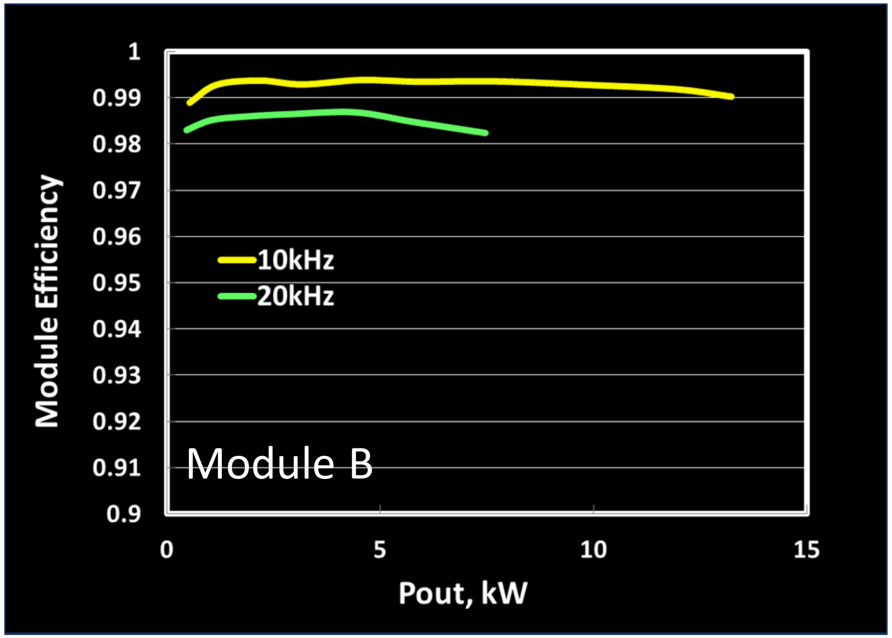

Module Base Plate
Steady State Temp ~ 29°C

$P_{out}$ = 21 kW
$P_{loss}$ = 120 W
Module Efficiency = 99.4%

# Module Efficiency

- Efficiency vs. Converter Power Out
- 50% Duty Cycle - Hard Switching




- Buck Converter power output limited by resistor load bank to 22 kW
- At 20kHz, thermal effects start to show, transient parasitics emerged which require further investigation

# Summary

- Demonstrated low loss *enhancement mode* 6.5 kV SiC JFET based power module
- Demonstrated 3.3kV switching at 15 kHz and 20 kHz in buck converter
- Module targets next generation high DC-Link voltage power conversion applications aimed at higher power densities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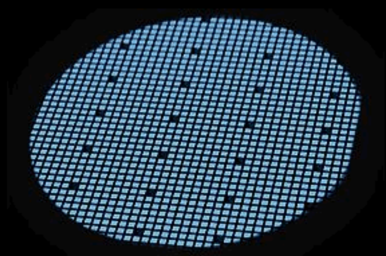

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# Thank You!

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