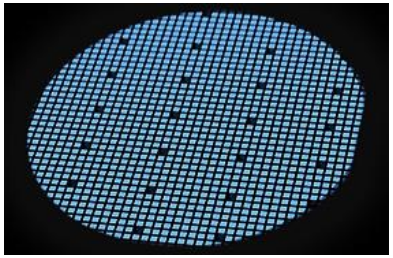
USCi
United Silicon Carbide, inc.




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

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U.S. DEPARTMENT OF ENERGY
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Power Semiconductor Solutions

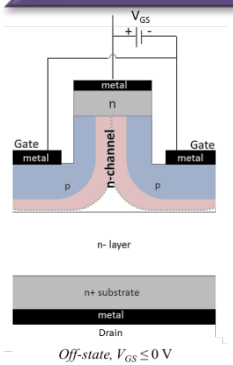
EESAT TECHNICAL CONFERENCE
SEPTEMBER 21-25, 2015
PORTLAND, OREGON

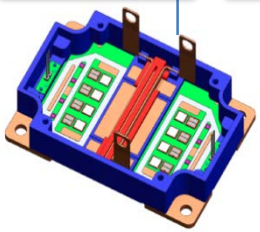
Contents

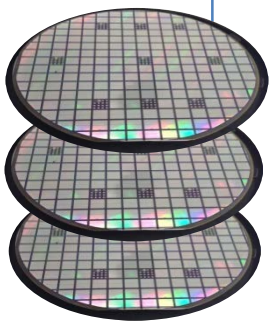
Project Overview

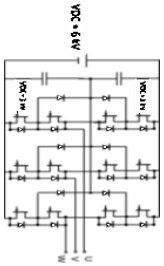
2012		2013	2013		2014				2015	
Q3	Q4	Q1	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Phase I			Phase II							

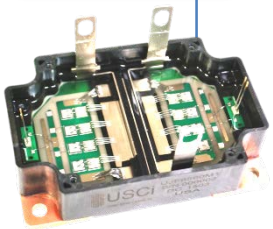
Device Design → **Epitaxial Growth Development** → **Module Design** → **6.5 kV Device Fabrication** → **Application Study** → **Module Assembly** → **Converter Testing**

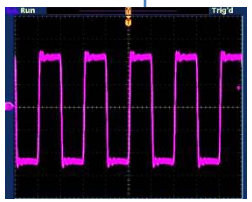


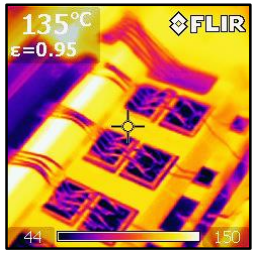












"Molecules to Megawatts"

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

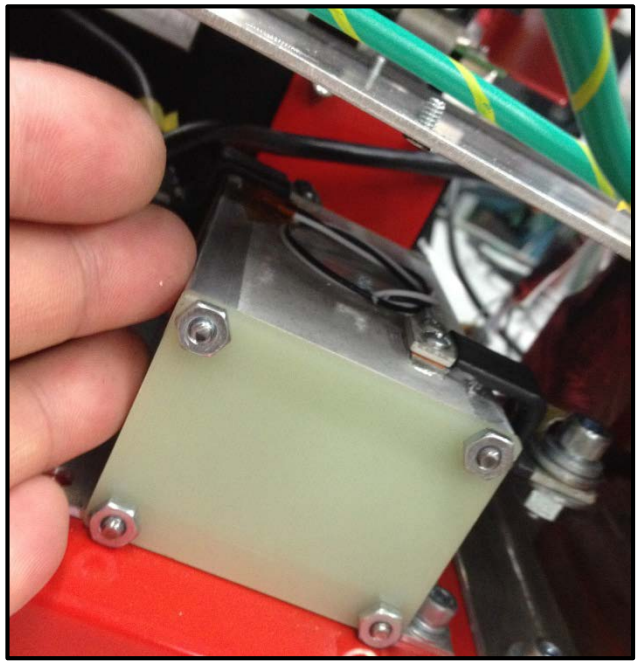
SiC JFETs can address 6.5kV applications, but with 20X lower losses than 6.5kV Si-IGBTs

- 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

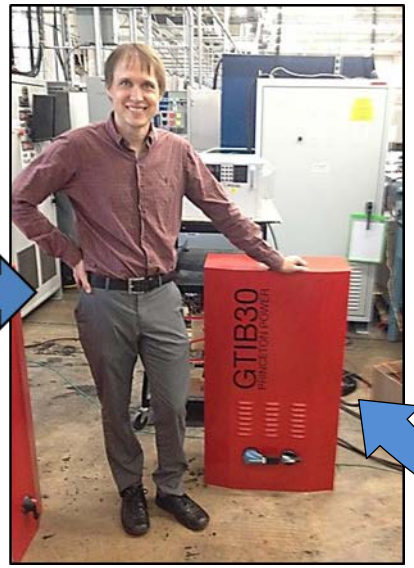
~10X Volume Reduction in Component!

Example: 30kW SiC Inverter

PRINCETON POWER SYSTEMS
Clean Power Made Simple™

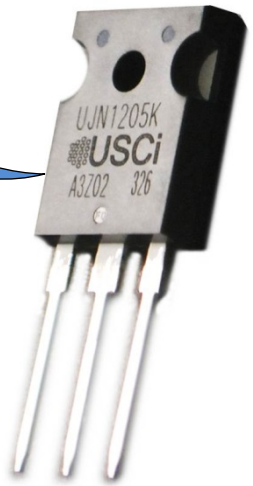
30kW Bidirectional Inverters

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

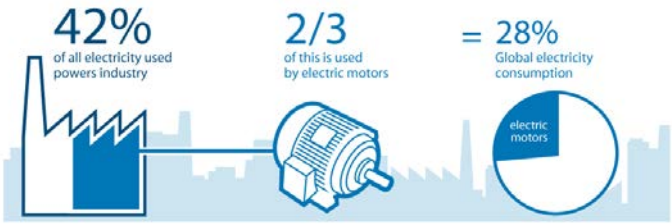


UJN1208K TO-247

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

6.5kV SiC JFET Module

- 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 Inverters
- Hybridization of Ships
- Flywheel: High Voltage Stators

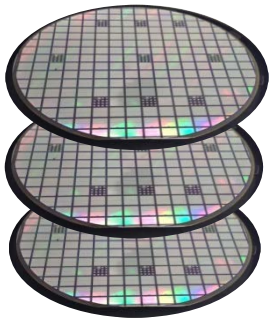
Trains

GVEA BESS
5kV DC-Link
(Alaska)

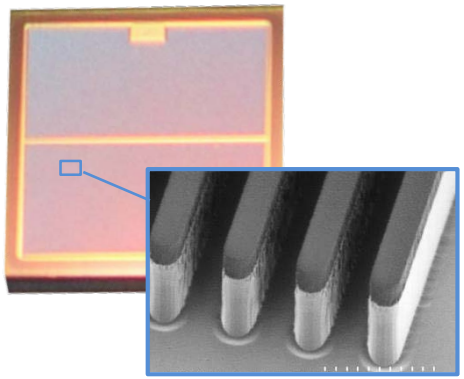
Contents

6.5 kV Enhancement Mode (Normally-Off) JFETs

100mm Wafers



6 X 6 mm

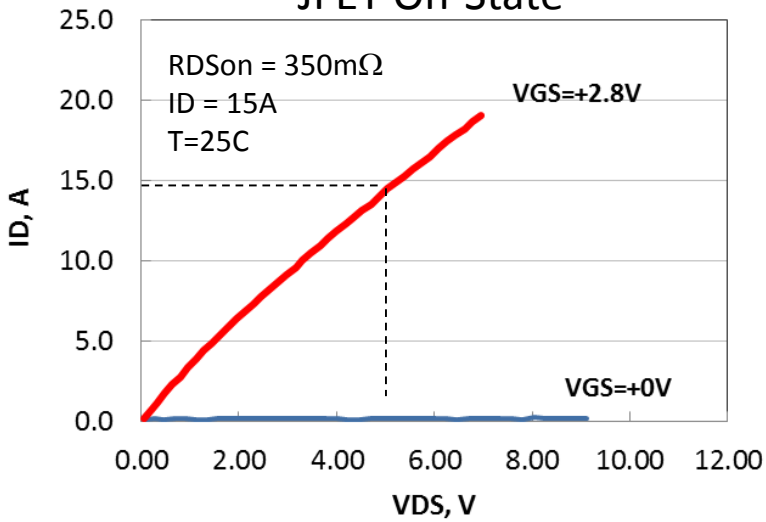


JFET Source Mesa

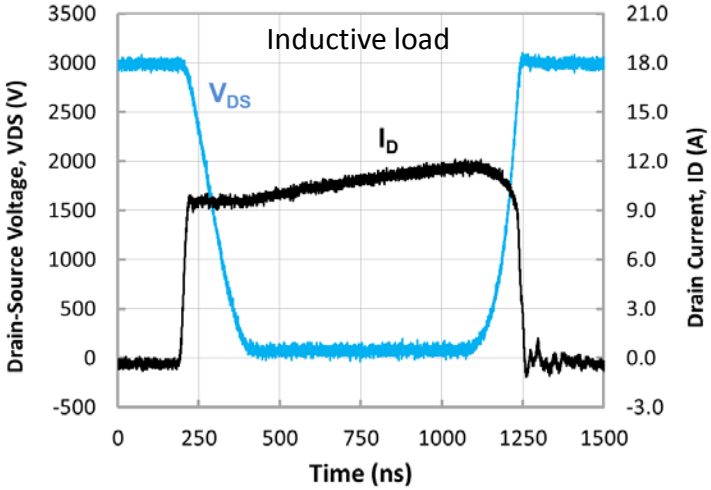
Parameter	Design Target	Meas.
Rise Time, t_r	150 ns	149 ns
Fall Time, t_f	100 ns	99 ns
Turn-on E_{on}	2.66 mJ	2.71 mJ
Turn-off E_{off}	0.9 mJ	1.54 mJ

Ultra Low Switching Losses

JFET On-State

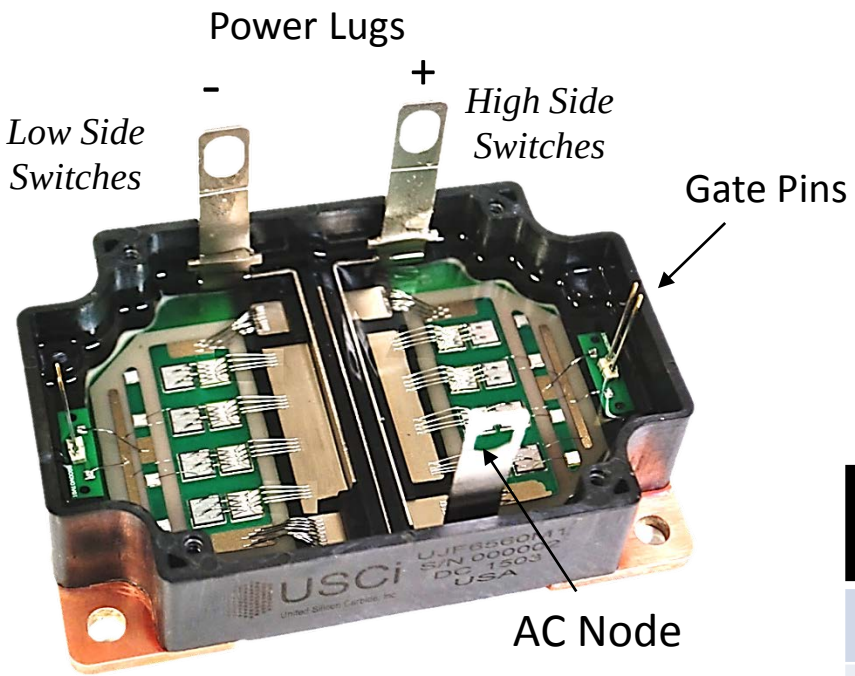


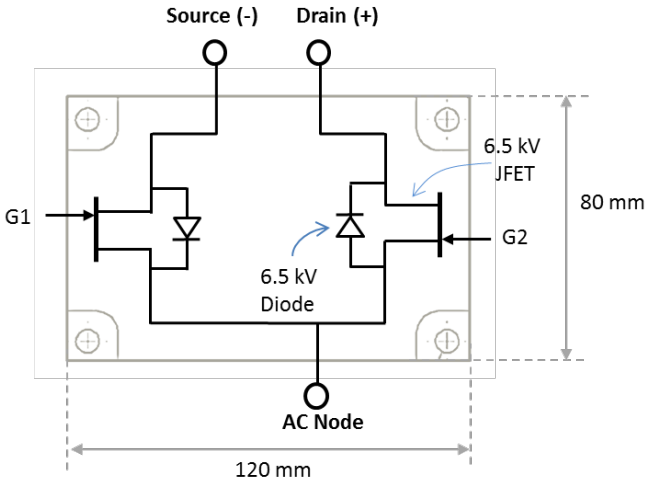
3kV -11A Device Switching



6.5 kV Half-Bridge Module

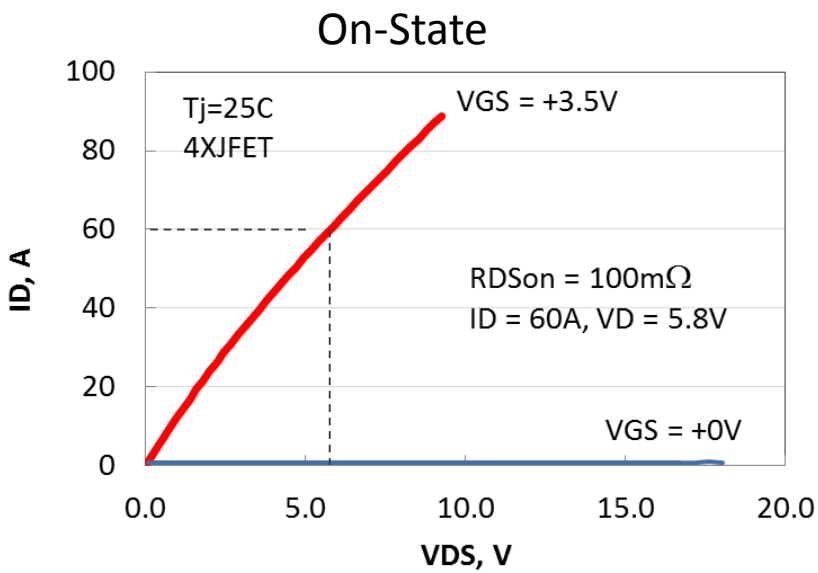
- 4 JFETs in parallel with 4 Diodes in antiparallel
  - Each switch set rated at 60A (4x15A)

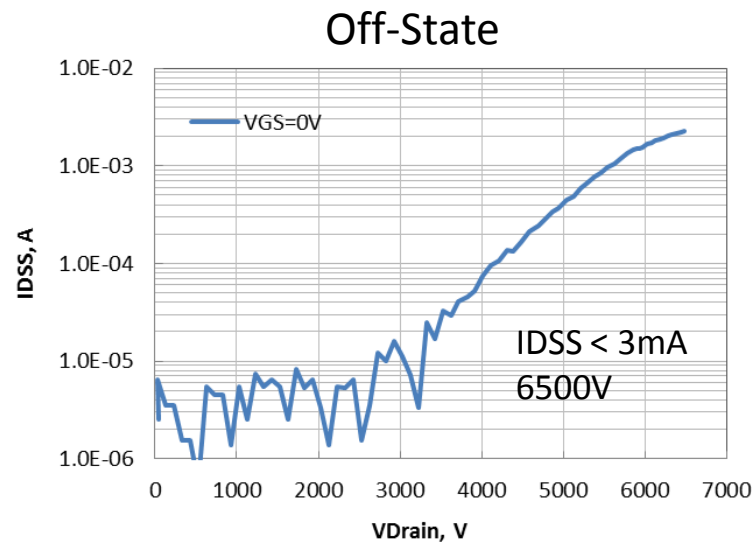


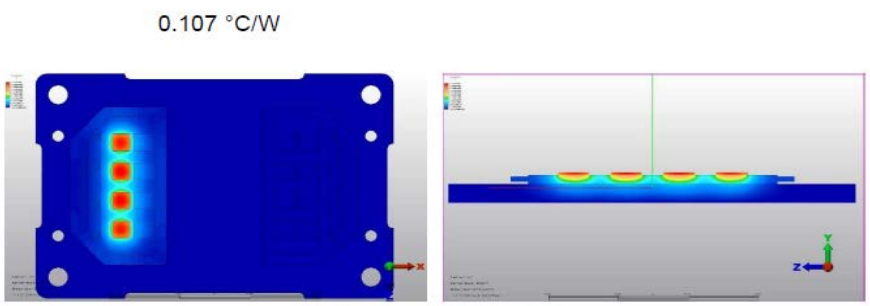


Module Rating		Typical Operation
Off-State	VDS = 6500V	VDS ~3300V
On-State	$ID_{(Cont,T=25C)}$= 60A	$ID_{(RMS, Max)}$ ~ 40A

Module Performance





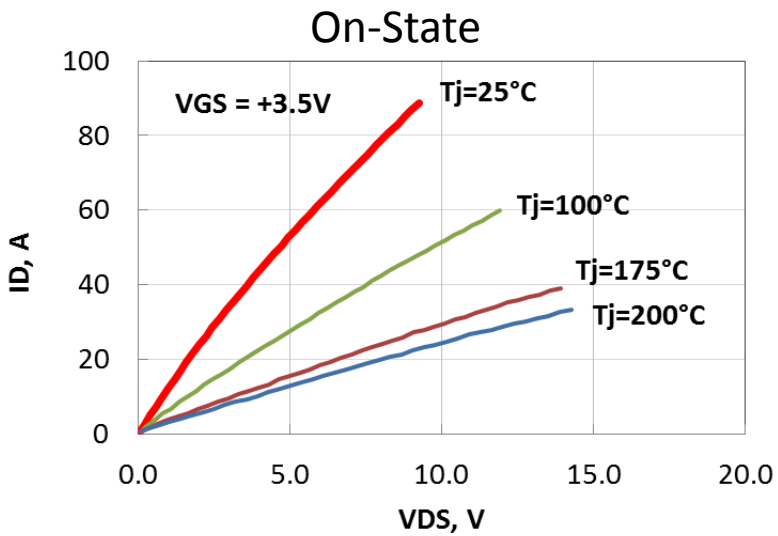


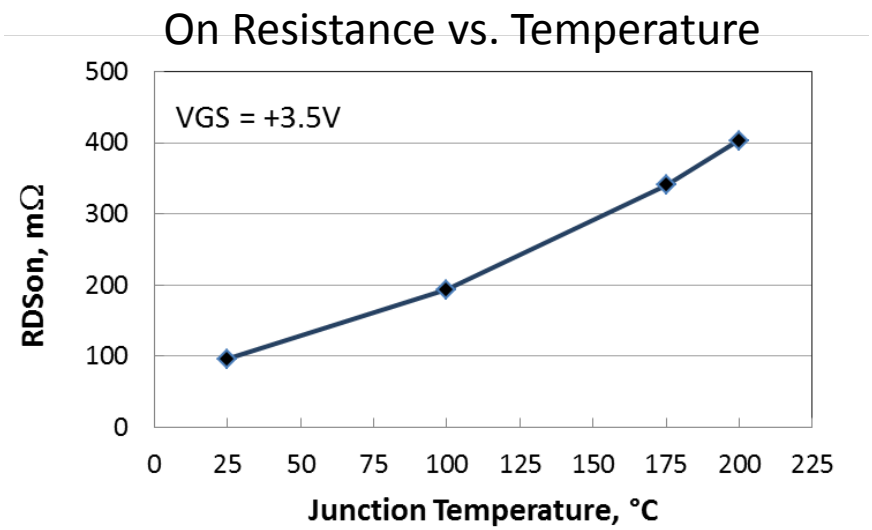
Optimized Chip Spacing

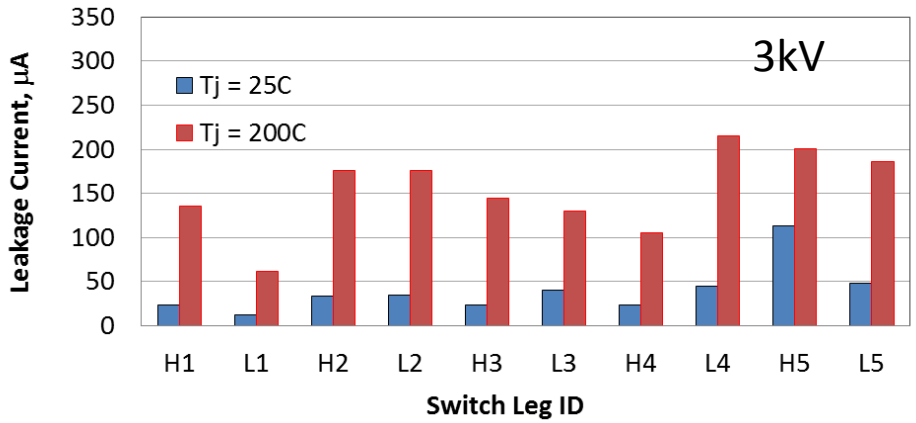
Thermal Resistance	Value (C/W)
$R_{TH\text{-}JC}$ (Junction-Case)	0.11
$R_{TH\text{-}HS}$ (Heatsink-Amb)	0.09
$R_{TH\text{-}Tot}$ (Junction-Amb)*	0.20
Max Power Dissipation	875W/per leg

*measured

High Temp Performance



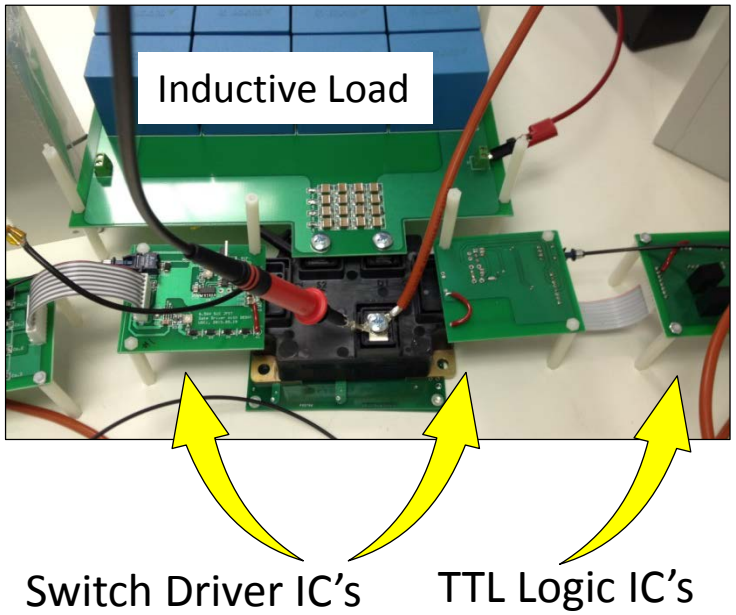




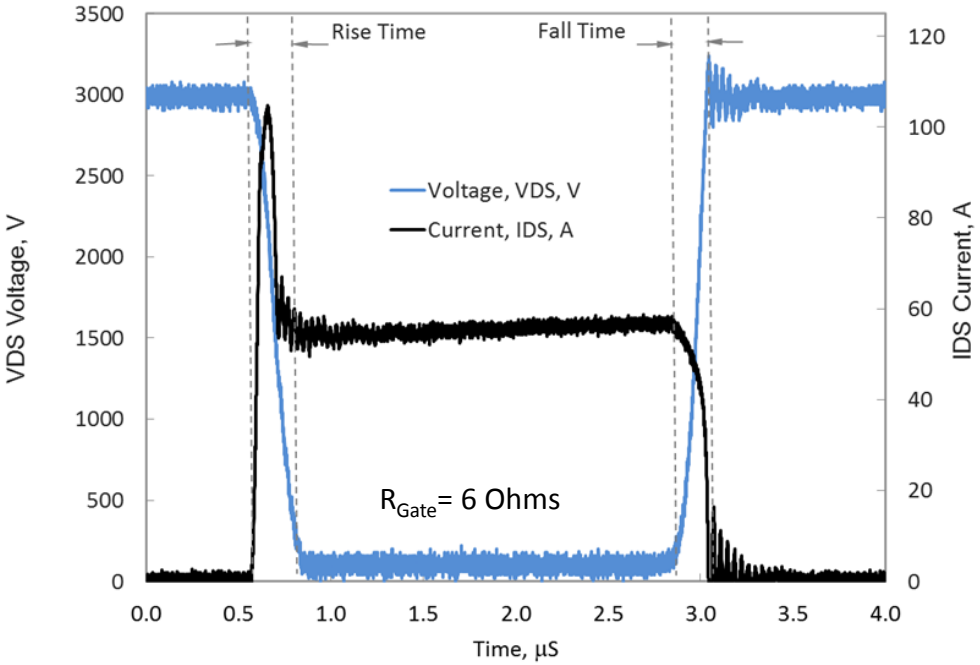
- Positive Temperature Coefficient
  - Good for paralleling chips
- Leakage < 250uA at 3kV for Tj=200°C

Module Switching

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



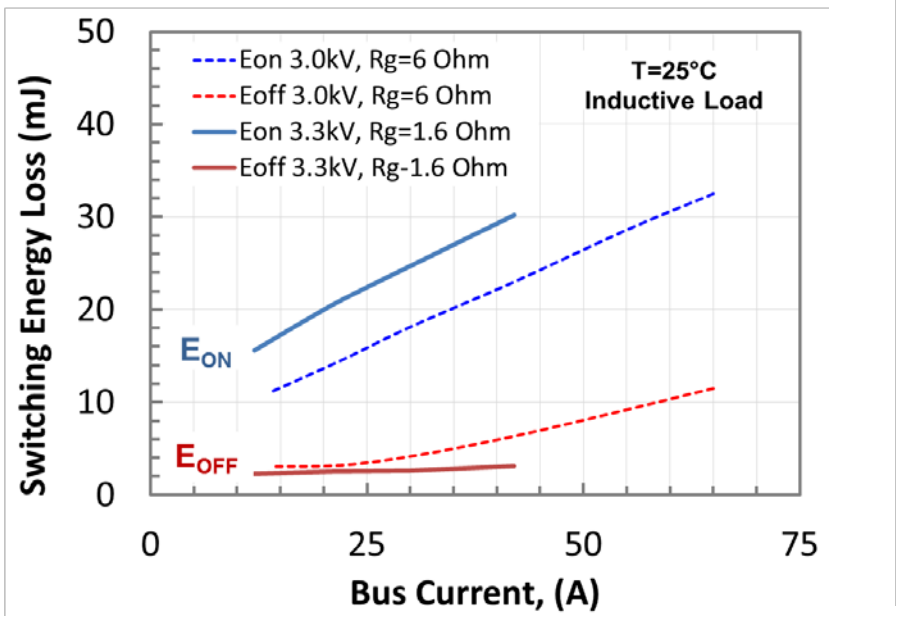
3kV – 60A Module Switching Waveform



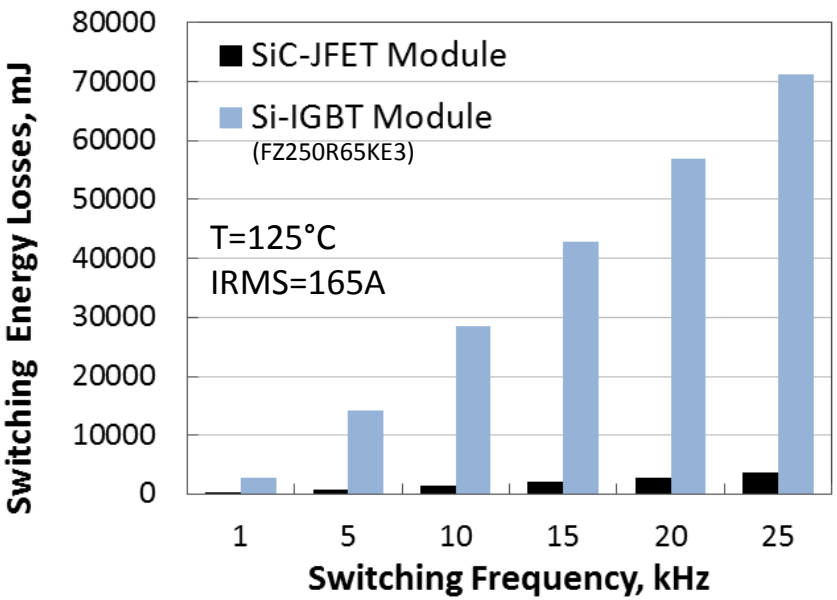
- Rise Time = 185ns, E_{on} = 28 mJ
- Fall Time = 130ns, E_{off} = 9.2 mJ

Module Losses

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



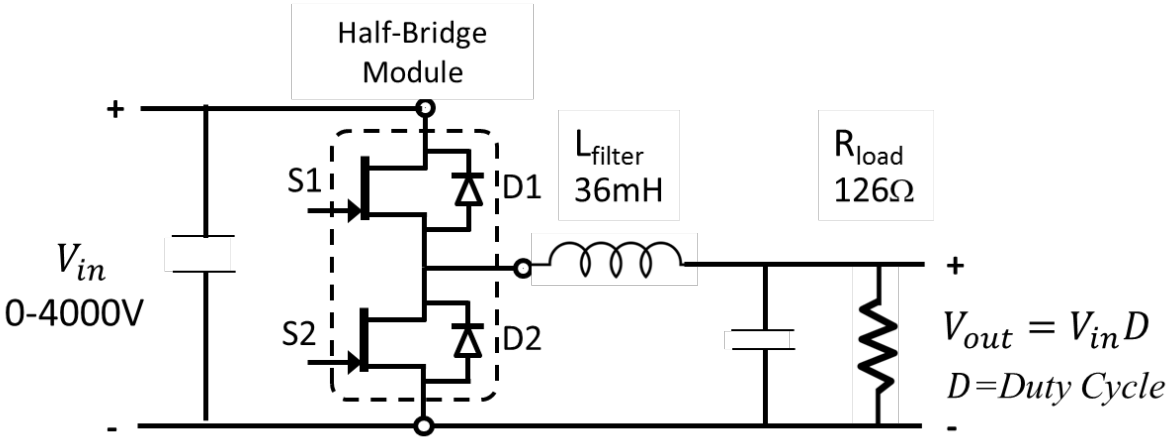
- Compare to 6.5kV 250A Si-IGBT
- 4 SiC Modules in parallel to scale to 240A max rating

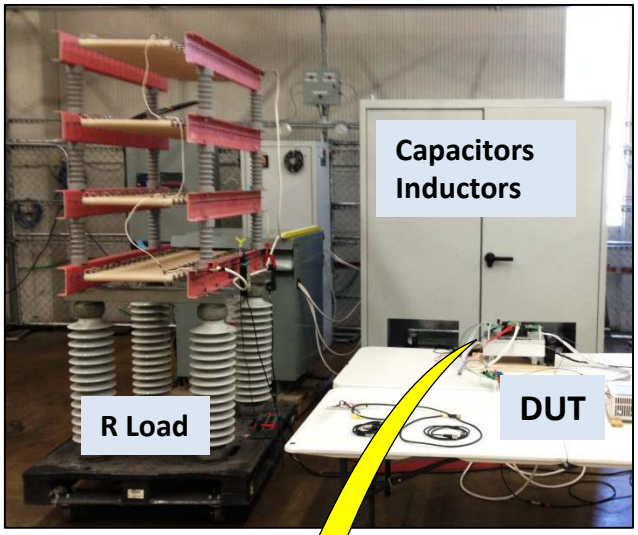


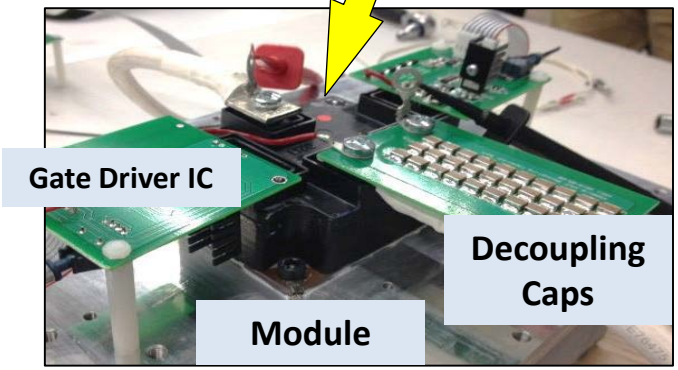
20X reduction in switching losses!

Contents

Buck Converter Testing



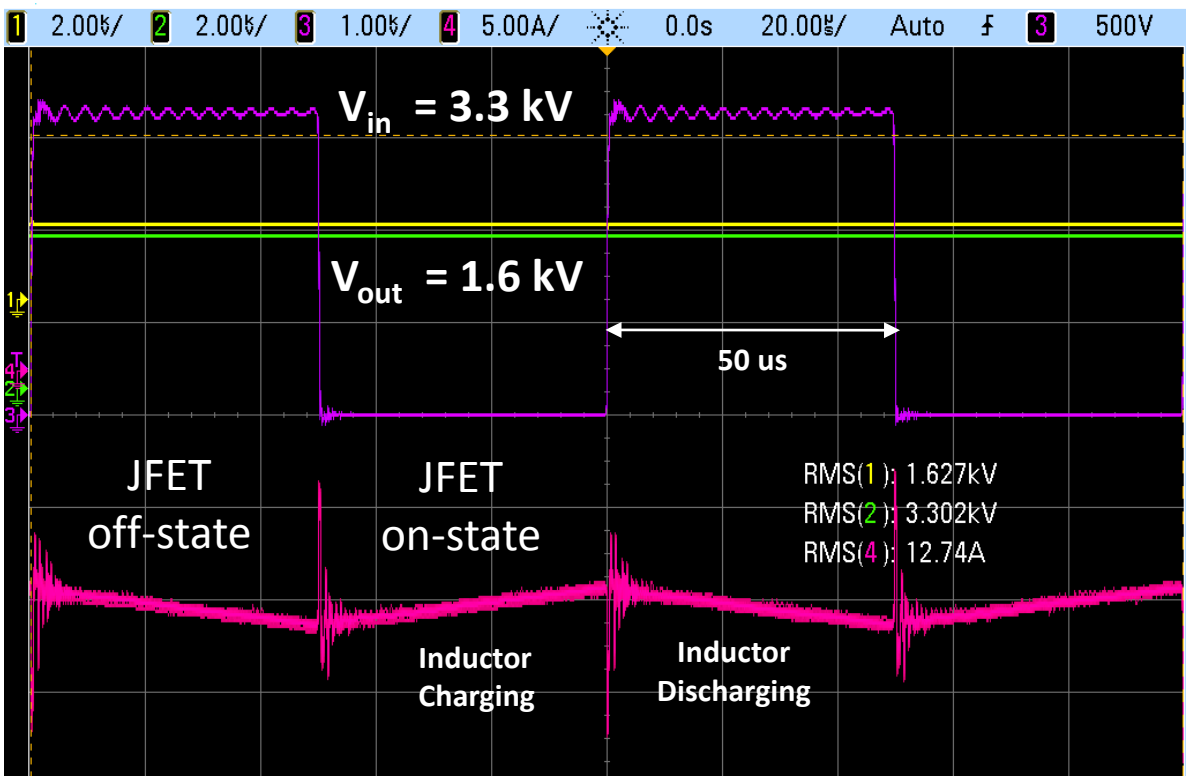


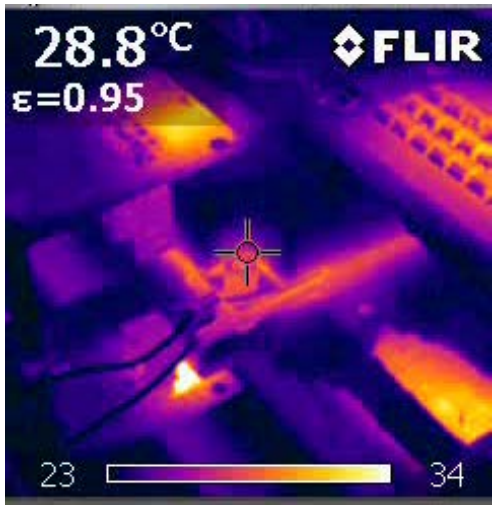


- DC/DC Down Converter
- **S1 On-State**
  - Current passes through switch, S1
- **S1 Off-State**
  - Current passes through diode, D2
- Steady-State Operation
  - Measure Module Temperature & Losses

Buck Converter Operation

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



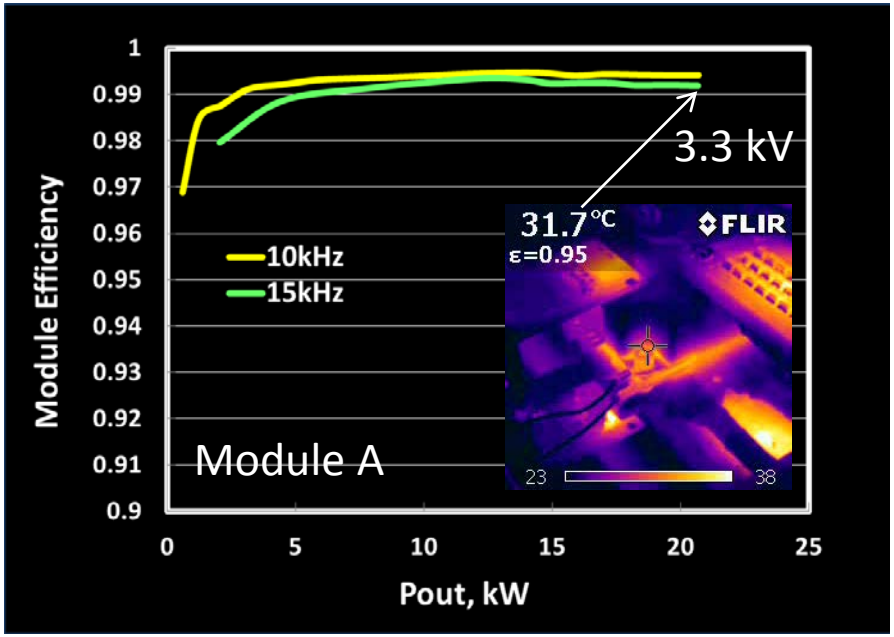


Module Base Plate
Steady State Temp ~ 29°C

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

Module Efficiency

- Module 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 10kHz, 15 kHz and 20 kHz in buck converter
- Module targets next generation high DC-Link voltage power conversion applications aimed at higher power densities

Acknowledgements

- USCi would like to thank **Dr. Imre Gyuk** of the DOE Energy Storage Program for funding and **Dr. Stan Atcitty** of Sandia National Labs for his technical contribution.

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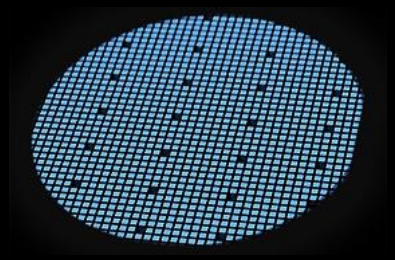

Thank You!

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USCi

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