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

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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
---|---
Q3  |  Q4  
Q1

Phase I

2013  |  2014  |  2015
---|---|---
Q3  |  Q4  |  Q1  |  Q2  |  Q3  |  Q4  |  Q1  |  Q2

Phase II

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

"Molecules to Megawatts"
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

- 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{DS(on)}$</td>
<td>80</td>
<td>mΩ</td>
</tr>
<tr>
<td>$V_{DS}$</td>
<td>1200</td>
<td>V</td>
</tr>
<tr>
<td>$T_{max}$</td>
<td>175</td>
<td>°C</td>
</tr>
</tbody>
</table>
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
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6.5 kV Enhancement Mode (Normally-Off) JFETs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Target</th>
<th>Meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise Time, $t_r$</td>
<td>150 ns</td>
<td>149 ns</td>
</tr>
<tr>
<td>Fall Time, $t_f$</td>
<td>100 ns</td>
<td>99 ns</td>
</tr>
<tr>
<td>Turn-on $E_{on}$</td>
<td>2.66 mJ</td>
<td>2.71 mJ</td>
</tr>
<tr>
<td>Turn-off $E_{off}$</td>
<td>0.9 mJ</td>
<td>1.54 mJ</td>
</tr>
</tbody>
</table>

Ultra Low Switching Losses

JFET On-State

RDSon = 350mΩ
ID = 15A
T=25°C

VDS, V

ID, A

0.00 2.00 4.00 6.00 8.00 10.00 12.00

VGS=+0V

VGS=+2.8V

3kV -11A Device Switching

Inductive load
6.5 kV Half-Bridge Module

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

**Module Rating**

<table>
<thead>
<tr>
<th>State</th>
<th>VDS, V</th>
<th>ID(Cont,T=25°C)</th>
<th>ID(RMS, Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-State</td>
<td>6500V</td>
<td>60A</td>
<td>VDS ~3300V</td>
</tr>
<tr>
<td>On-State</td>
<td></td>
<td></td>
<td>~40A</td>
</tr>
</tbody>
</table>
Module Performance

On-State

- Tj=25°C
- RDSon = 100mΩ
- ID = 60A, VD = 5.8V
- VGS = +3.5V
- VGS = +0V

Off-State

- IDSS < 3mA
- 6500V

Thermal Resistance

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

*measured
High Temp Performance

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

**On-State**

- VGS = +3.5V
- Tj=25°C
- Tj=100°C
- Tj=175°C
- Tj=200°C

**On Resistance vs. Temperature**

- VGS = +3.5V

**Leakage Current vs. Switch Leg ID**

- 3kV
- Tj = 25°C
- Tj = 200°C
- 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, $E_{on} = 28\, \text{mJ}$
- Fall Time = 130ns, $E_{off} = 9.2\, \text{mJ}$

- Inductive Load

$R_{Gate} = 6\, \text{Ohms}$
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!
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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

\[ V_{out} = V_{in}D \]
\[ D = \text{Duty Cycle} \]
Buck Converter Operation

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

Module Base Plate
Steady State Temp ~ 29°C

$P_{\text{out}} = 21\text{ kW}$
$P_{\text{loss}} = 120\text{ W}$
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

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Thank You!

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