High Voltage Silicon Carbide Power Devices

February 9, 2010

John W. Palmour

Cree, Inc.
4600 Silicon Drive
Durham, NC 27703; USA
Tel.: 919-313-5646
Email: john_palmour@cree.com
SiC MOSFETs and Schottky Diodes show Zero $Q_r$

Reduced Losses Using SiC JBS Diode

SiC JBS Diode Switching Waveform

Si PiN Diode Reverse Recovery
Commercially Available SiC JBS Rectifiers

- Cree ZERO RECOVERY™ Rectifier Product Family
  - 600V 2A, 4A, 6A, 8A, 10A & 20A
  - 1200V 5A, 10A, 20A, 50A

- Major Applications
  - Power Factor Correction (PFC) in Switch Mode Power Supplies (SMPS)
  - Boost Converter and Inverter Section for solar conversion
  - Anti-Parallel rectifier in Motor Control
### Extremely Low Field Failure Rate Of Cree SiC JBS Diodes

**Cree Field Failure Rate Data since Jan. 2004**

<table>
<thead>
<tr>
<th>Product</th>
<th>Device Hours</th>
<th>FIT (fails/billion hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSDxxx60</td>
<td>75,200,000,000</td>
<td>0.6</td>
</tr>
<tr>
<td>CSDxxx60</td>
<td>42,700,000,000</td>
<td>0.1</td>
</tr>
<tr>
<td>CSDxxx60</td>
<td>7,060,000,000</td>
<td>0.1</td>
</tr>
<tr>
<td>CSDxxx60</td>
<td>2,440,000,000</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>127,400,000,000</strong></td>
<td><strong>0.4</strong></td>
</tr>
</tbody>
</table>

- 2 largest Cree Customers: “Your SiC parts are much more reliable than the Silicon parts we were using.”
Growth in Commercial Production of SiC JBS Diodes at Cree

- Over 2.4x Reduction in Price of SiC JBS Diode – 3 Factors
  - Higher Quality SiC Material
  - Larger Production Volumes
  - Increase SiC Wafer Size From 3 inch to 100 mm Diameter

In FY2010 Cree will Ship 70 GVA of SiC JBS Diodes
⇒ 120% Increase Over 2009
⇒ 68% CAGR since 2005

MVA of Cree SiC Sales

Creating Technology That Creates Solutions
Lighting is cool.....

BUT...SiC power devices affect the other 80% of all electricity used

Cree’s Schottky diodes have already saved > $200M in electricity worldwide.

At current shipping rates, we have already eliminated the need for 1 coal fired power plant. We could save >240 more.
Total Power Loss Comparison of 1.2kV / 10A SiC DMOSFET vs. Si IGBT (IRG4PH40KD)

\[ P_{\text{Total}} = \text{On-State Power} + \text{Turn-off Power} + \text{Turn-on Power} \]
\[ P_{\text{Total}} = I \cdot V \cdot \text{Duty Cycle} + (W_{\text{off}} + W_{\text{on}}) \cdot \text{frequency} \]

Calculation Parameters
- \( T = 150^\circ \text{C} \)
- \( I = 10 \text{ Amps} \)
- Duty Cycle = 50%

Si IGBT Is Impractical at High Frequencies

>10x increase in frequency

80% Power Savings

Creating Technology That Creates Solutions
Dramatic Increase in Efficiency of 3-Phase Solar Inverter Using 1200V SiC DMOSFET

- 2.4% Increase in Efficiency of 3-Phase Solar Inverter Achieved Using Cree 1200V SiC DMOSFET
- Replaced 1200V Si IGBTs in Solar Inverter With 1200V SiC DMOSFETs w/o Optimization
- Significant Cost Savings
  - 81 Euro/yr in Northern Europe
  - 164 Euro/yr in Southern Europe
10kV/10A SiC DMOSFETs for 10kV/120A Half-H-Bridge Modules Capable of 20kHz Operation

10kV/10A SiC DMOSFETs on 3-inch 4HN-SiC Wafers Moving to 100 mm

10kV/10A SiC DMOSFET 8.1 x 8.1 mm Die

Comparison of Combined Power Loss for 10kV/10A SiC DMOSFETs & 2x 6.5kV SiC IGBT Operating at 20 kHz Switching Frequency

<table>
<thead>
<tr>
<th>Device</th>
<th>Breakdown Voltage (kV)</th>
<th>20 kHz Switching Loss (W/cm²)</th>
<th>Conduction Loss @ 100°C (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cree SiC DMOSFET</td>
<td>10 (12)</td>
<td>160</td>
<td>100</td>
</tr>
<tr>
<td>2x 6.5kV ABB Si IGBT 5SMX 12M6500</td>
<td>12</td>
<td>2900</td>
<td>182</td>
</tr>
</tbody>
</table>

DARPA/ONR HPE-III 10kV/120A SiC DMOSFET/JBS Diode Half H-Bridge Module Capable of 20 kHz Operation

10kV/10A SiC DMOSFETs Are Essential for 20 kHz Switching at 10kV
10 kV, 100 A SiC MOSFET Modules

9% Weight and 12% Volume vs IGBT module

SiC Module
10 kV
100 amps

IGBT Module
13.5 kV
100 amps
Transformer Size Shrinks Dramatically

DARPA/ONR Transformer for SiC SSPS

20 kHz Transformer

- 250 kVA 20 kHz transformer
- 16” high
- 75 lbs

60 Hz Transformer

- 330 kVA 60 Hz transformer
- 55” high
- 2700 lb
What Is Next for High Voltage SiC Power Devices?

• 10 kV ~ Upper Limit of SiC Unipolar Devices
  –DMOSFETs and Schottky diodes

• Higher Voltage ⇒ Bipolar Devices
  –Si IGBT Replace Si DMOSFET at > 1kV

• For SiC Devices, This Holds True for >10 kV
  –SiC breakdown field 10x that of silicon

Over ~ 10kV - We Need SiC IGBTs, GTOs and PiN Diodes
Comparison of SiC n-IGBTs and Si IGBTs

• SiC IGBTs Are Superior to Si IGBTs at Higher Voltages
  – 12kV SiC n-IGBTs Have >3x Lower $R_{on,sp}$ Than 6.5kV Si IGBTs
  – SiC n-IGBTs Have Much Lower Forward Voltage ($V_F$) & Higher Current Than Si IGBTs at Same BV
  – 12kV SiC n-IGBTs Have 4x Faster Switching Speed and >4x Lower Switching Loss than 6.5kV Si IGBTs

12kV SiC n-IGBT Switching Measurement

- $V_{CE}$
- $J_C$
- $t_{off, delay} \approx 400$ nsec
- $t_{fall} \approx 100$ nsec
- $90\%$ and $10\%$ marks
12kV SiC n-IGBT Boost Converter

12kV SiC n-IGBTs Used to Demonstrate 5 kV / 5 kHz Boost Converter With 85% Efficiency

SiC n-IGBT/JBS Diode
5kV/5KHz Boost Converter

Input
V_IN = 516 V
I_IN = 1.41 A
P_IN = 728 W

Output
V_OUT = 5 kV
I_OUT = 0.12 A
P_OUT = 617 W
Duty Cycle 90%

SiC 12 kV n-IGBT/JBS Diode
5kV / 5 KHz Boost Converter
Efficiency = 85%

Creating Technology That Creates Solutions
Grid Scale Storage

Today using Silicon IGBTs:

- Battery Energy Storage System: 400 V
- Bi-directional DC/DC Boost Converter: 750 V
- Voltage Source Converter: 3Ø, 100 kVA
  - 3Ø, 480 V
  - 3Ø, 13.6 kV

60 Hz Transformer Required for Interconnection to 13.6 kV Distribution Grid

Creating Technology That Creates Solutions
Grid Scale Storage w/ SiC Interface

Transformer-less Intelligent Power Substation (TIPS)

Battery Energy Storage System

Bi-directional DC/DC Boost Converter

Voltage Source Converter 3ø, 100 kVA

Grid

400 V

20 kV

3ø, 13.6 kV

Silicon Carbide 1.2 kV MOSFET and 10 kV MOSFET or 15-20 kV IGBT

No 60 Hz Transformer Required for Interconnection to 13.6 kV Distribution Grid
SiC for High Voltage Devices

- SiC production and reliability proven at low voltages (600-1200V) and running in high volume
- SiC MOSFETs nearing production at 1.2 kV, and 10 kV devices are proven and circuit demos show incredible performance
- For higher voltage (>10 kV), GTOs and IGBTs have been demonstrated
- SiC can enable high voltage transformerless interfaces for Grid-Scale energy storage