From SiC MOSFET Devices to MW-scale Power Converters

Ljubisa Stevanovic, CTO of Silicon Carbide Works
GE Global Research
Acknowledgment:

Peter Losee, Alexander Bolotnikov, Stacey Kennerly, Brian Rowden, Arun Gowda, Tobias Schuetz, Fabio Carastro, Maja Harfman-Todorovic, Owen Schelenz, Thomas Brueckner, Robert Roesner, Peter Sandvik, Jeff Slotnick, Rajib Datta, Ravi Raju, Jorge Mari, Michael Schutten, David Esler, Xu She, Fengfeng Tao, Robert Thomas and Philip Cioffi

GE Global Research and GE Power Conversion
Overview

SiC MOSFET Chip
• Excellent performance
• Excellent reliability
• Extremely rugged

Module
• Benchmark performance: 1.7kV, 600A, 175°C
• Ultra-low Lσ for fast switching
• Advanced GDU & protection

Power Block
• Simple 2-level bridge
• High power density
• Scalable to multi-MWs
  • Perfect current sharing
  • Clean waveforms

Applications
• Higher efficiency
• Smaller footprint
• Better reliability

GE SiC advantage... vertical integration from chip to converter
SiC MOSFET Devices
Qualification per AECQ101 at 200°C
GE Gen-1 MOSFETs: TO247 1.2kV/30A & TO268 1.2kV/65A

Pass/fail criteria:
• ΔV_{TH} = +/-20% Max
• ΔR_{ON} = +/-20% Max
• ΔI_{DSS,1200} < 5x Max
• 
• 
→ 0/77 failures

HTGB: 1000 hr, 200°C, V_{GS}=23V:
✓ passed

HTRB: 1000 hr, 200°C, V_{DS}=960V:
✓ passed

1000 temp. cycles (-55 to +200°C):
✓ passed

P. Losee et al. “1.2kV Class SiC MOSFETs with Improved Performance over Wide Operating Temperature,” 2014 ISPSD
SiC MOSFET Performance Benchmarking

R&D Focused Metrics

Product Focused Metrics:
$R_{DS,On} @ 150^\circ C$ based on total die area

Great progress from ‘13-'16

R&D benchmarking alone is not sufficient

One must also consider:
- Practical operating conditions
- Chip overhead
- Manufacturability, Yield, Packaging
- Reliability, Ruggedness
1.7kV SiC MOSFET: 29mΩ, 70A @ T_{J}=25^\circ C

- Chip size: 4.5mm x 4.5mm (20.25mm^2)
- 70A Rated @ T_{C}=25^\circ C
- T_{J,MAX} = 175^\circ C (package limited)
- R_{DS,On}=29mΩ @(70A, T_{J}=25^\circ C), 54mΩ @150^\circ C
- Normally-off w/ avalanche limited BV @2150V
1.7kV SiC MOSFET Avalanche Ruggedness

Unclamped Inductive Switching (UIS)

- 1.7kV, 70A SiC MOSFET: $E_{AV} > 8J/cm^2$
- $E_{AV}$ distribution is an indication of robust design-process
1.7kV MOSFET Short-Circuit Withstand Time

- Important for system safety, Si IGBTs typically have SCWT ≈ 10\(\mu s\)
- SiC MOSFETs not as robust as the IGBTs, need faster (\(\sim 1\mu s\)) protection
- TO247-packaged 1.7kV, 70A MOSFET test results show SCWT ≈ 3\(\mu s\)
MOSFET active area: $A_{\text{act}} = 7.2\, \text{cm}^2$
corresponds to following module ratings:
- 2 x 1.2kA for 1.2kV version,
- 2 x 1.0kA for 1.7kV,
- 2 x 750A for 2.2kV,
- 2 x 650A for 2.5kV,
- 2 x 450A for 3.3kV
(2 x denotes dual module configuration)
## High Temperature Reverse Bias @ 175°C

### 1.7kV, 70A TO247 Discretes

<table>
<thead>
<tr>
<th>Test Condition (1360V &amp; 1700V)</th>
<th>Sample Size</th>
<th>Stress Time</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>80% HTRB</td>
<td>n=16</td>
<td>1133 hrs</td>
<td>0 / 16 Fail</td>
</tr>
<tr>
<td></td>
<td>n=82</td>
<td>1076 hrs</td>
<td>0 / 80 Fail</td>
</tr>
<tr>
<td>100% HTRB</td>
<td>n=32</td>
<td>1046 hrs</td>
<td>0 / 32 Fail</td>
</tr>
<tr>
<td></td>
<td>n=80</td>
<td>1076 hrs</td>
<td>1 / 82 Fail</td>
</tr>
</tbody>
</table>

1 failure out of 210 devices (IDSS leakage increase over 5x between t=0h & t=1,000h)
Low Inductance 1.7kV Power Module
1.7kV SiC MOSFET Dual Module

- 1.7kV, up to 600A, $T_{J_{\text{MAX}}}=175^\circ \text{C}$
- Compatible with E3-style footprint
- 12 MOSFET chips per switch
- Designed for low inductance: 4.5nH
- Body diode + 3Q MOSFET for low cond. losses

1.7kV Gen-1 MOSFET Module, $V_{gs}=20\text{V}$

![Graph showing $I_D$ vs $V_{DS}$ for different temperatures](image)

RdsON $V_{gs}=20\text{V}$ 200A SiC Gen3 vs. Gen1 MOS


© 2017 General Electric Company - All rights reserved
Multi-plots as Function of Load Current

Turn off @ 150°C, 1000V

51A - 546A, lower device

Turn on @ 150°C, 1000V

53A - 519A, lower device

51A - 533A, upper device

56A - 531A, upper device
1.7kV SiC Module Switching Losses

Lower Switch @1kV, 150°C

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Switching Test Conditions</th>
<th>$E_{\text{ON}}$ (mJ)</th>
<th>$E_{\text{OFF}}$ (mJ)</th>
<th>$E_{\text{REC}}$ (mJ)</th>
<th>$E_{\text{SUM}}$ (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE Gen-1 1.7kV SiC</td>
<td>1kV, 450A, 150C, $R_{\text{ON}}=R_{\text{OFF}}=4.3\Omega$</td>
<td>21.5</td>
<td>16.5</td>
<td>6</td>
<td>44</td>
</tr>
<tr>
<td>FF450R17ME4_B11</td>
<td>900V, 450A, 150C, $R_{\text{ON}}=R_{\text{OFF}}=3.3\Omega$</td>
<td>145</td>
<td>170</td>
<td>125</td>
<td>440</td>
</tr>
</tbody>
</table>

Compared to Si IGBT, SiC module switching losses are 10 times lower
Performance and Cost Advantage

- Less heat to manage: 50% lower total losses vs. IGBT
- Higher temp. capability: 25°C higher junction temp. vs. IGBT
- Higher frequency: 10X higher frequency vs. IGBT

Si IGBT Modules

SiC MOSFET Modules

Increase current rating by 40% at 3x higher switching frequency
MW-scale SiC Products
World’s First MW-scale all-SiC PV Inverter

- 2x 1 MW units with SiC MOSFET modules
- Operating in utility scale solar plant since Nov. 9, 2016
- Up to: 10MWh daily energy production, ~100kWh incremental vs. Si
- Risk reduction for the high volume 2.5MW all-SiC product
Anatomy of the SiC PV Inverter

- 1.7kV SiC MOSFET modules
- Simple 2-level bridge, hard switching at 8kHz
- Synchronous rectifier mode
- 3 parallel modules sharing single gate drive unit
Anatomy of the SiC PV Inverter

- DC bus located in the center
- Hard paralleling of 2 x 3 modules
- Total commutation loop inductance < 15nH
- Air channel in the back
- 800mm-wide cabinet
Anatomy of the SiC PV Inverter

Positive temp-co, symmetrical layout result in excellent static and dynamic current sharing:

- within 3x parallel modules
- between top & bottom bridges
Anatomy of the SiC PV Inverter

- SiC efficiency validated
  - module losses reduced by over 50% vs. Si IGBTs
- BOS becoming critical
  - AC reactor core losses
  - AUX components also impacting efficiency rating (fans, power supplies, ...)

Converter efficiency, early prototype to validate SiC entitlement (AC reactor core losses high / not optimized for 8kHz)
SiC PV Inverter Field Demo - EMI

- Free field measurements
- Converter connected to PV array
- Operating at 1MW
SiC PV Inverter Field Demo

Timeline:
- from initial lab prototype in 2015
- to field demo in 2016
- to new product introduction in 2017

GE LV5+ Series PV inverter product line:
- First all-SiC MW-scale converter
- $1.5 \text{kV}_{\text{DC}} / 600 \text{V}_{\text{AC}}$, simple 2-level bridge
- 99% weighted efficiency
- simplified air cooling
- On target cost to meet business needs
## LV5+ Series Solar Solutions

### GE’s NEW 1500V LV5+ SiC PV INVERTER

![Inverter Image]

### Technical Data: LV5+ Solar Inverter

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter Efficiency</td>
<td>99% EU and 99.2% MAX</td>
</tr>
<tr>
<td>MPP Voltage</td>
<td>875 VDC to 1300 VDC</td>
</tr>
<tr>
<td>AC Power</td>
<td>2500 KW @ 50°C &amp; COS((\Phi))=1</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>600 VAC</td>
</tr>
<tr>
<td>Fuses</td>
<td>24 DC fuses (per input)</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-20°C to +50°C</td>
</tr>
<tr>
<td>Dimensions</td>
<td>W x H x D (M) = 2.4M x 2.9M x 2.0M</td>
</tr>
<tr>
<td>Weight [KG]</td>
<td>&lt; 2000 KG</td>
</tr>
</tbody>
</table>

### E-HOUSE: MAXIMIZING LIFETIME VALUE

![E-House Image]

### Technical Data: LV5+ Solar EHouse Solution

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter Efficiency</td>
<td>99% EU and 99.2% MAX</td>
</tr>
<tr>
<td>MPP Voltage</td>
<td>875 VDC to 1300 VDC</td>
</tr>
<tr>
<td>AC Power</td>
<td>2500 KW @ 50°C &amp; COS((\Phi))=1</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>11 to 35 KV</td>
</tr>
<tr>
<td>Fuses</td>
<td>24 DC fuses (per input)</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-20°C to +50°C</td>
</tr>
<tr>
<td>Dimensions</td>
<td>W x H x D (M) = 2.4M x 2.9M x 6.1M</td>
</tr>
<tr>
<td>Weight [KG]</td>
<td>&lt; 12 000 KG</td>
</tr>
</tbody>
</table>
LV5⁺ ...optimizing OPEX

FULLY INTEGRATED SOLAR SOLUTION

- $316k/100MW* with air-filterless design. Reliable operation in harsh & dirty (sand, dust) environments
- Optional sleep feature** eliminates stand-by transformer losses at night. Up to $820k/100MW* lower OPEX
- Reduced commissioning time

$316k / 100MW OPEX SAVINGS, WITH $820K INCR. OPPORTUNITY

*all values undiscounted cashflow, 30 year project life with 2500MWh AEP baseline

**currently available for systems up to 24kV

*unrelated to SiC technology
LV5\textsuperscript{+}...boosting performance

**Higher Inverter Efficiency...**

**...Yields Higher Annual Energy Production**

---

**Country** | **Incr. AEP** | **Incr. value/100MW\(^*\)**
---|---|---
USA | 0.9\% | $2.2M
Mexico | 1.0\% | $2.5M
Brazil | 0.5\% | $1.2M

---

**Country** | **Incr. AEP** | **Incr. value/100MW\(^*\)**
---|---|---
Spain | 0.8\% | $2.0M
Saudi Arabia | 1.2\% | $3.0M
India | 1.5\% | $3.7M

\(^*\)All values undiscounted cash flow, 30 year project life with 2500MWh AEP baseline
Summary

• Advanced SiC MOSFETs and modules
• Switching losses 10x lower than Si IGBTs
• Efficient, reliable and rugged
• Simple 2-level bridge at the core of LV5+, the 2.5MW, 99% efficient SiC PV Inverter
Thank you!