Opportunities for Wide Bandgap Semiconductor Power Electronics for Hydrogen and Fuel Cell Applications

Presenters:
Jeff Casady and John Palmour of Cree Inc.

DOE Hosts:
Eric Miller and Anant Agarwal
Question and Answer

• Please type your question into the question box

hydrogenandfuelcells.energy.gov
DOE Fuel Cell Technologies Office covers Research, Development, Demonstration & Deployment


### DOE R&D

**Fuel Cell System Cost**

Transportation projected to (500,000 units per year)

- Status Today
- Goal

50% reduction vs. 2006 ($55/kW)

**Electrolyzer Stack Costs**

80% reduction since 2002

### DOE Demonstrations

- >180 FCEVs
- 25 stations
- 3.6 million miles traveled
- World’s first tri-gen station (250 kW on biogas, 100 kg/d H2 produced)

### Deployments

- DOE Recovery Act
- Market Transformation Projects
- Government Early Adoption (DoD, FAA, California, etc.)
- Tax Credits: 1603, 48C

Recovery Act & Market Transformation Deployments

~1,600 fuel cells deployed

>11,000 follow on orders
Fuel Cell Stack and PEM Electrolyzer System Cost Components

Power electronics and stacks are large cost components of the PEM electrolyzer system while catalyst is a key challenge for fuel cell stack cost.

Catalyst accounts for >45% of total system cost

*For PEMFC Stack cost, 500,000 units per yr. Cost is shown as $/kW-net.

Power Electronics, H₂ management and the stacks accounts for ~70% of PEM electrolyzer total system cost.
WBG Revolution in Power Electronics

Anant Agarwal, EERE/DOE
What are Wide Band Gap (WBG) Semiconductors?

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.1 eV</td>
<td>3.25 eV</td>
<td>3.4 eV</td>
</tr>
<tr>
<td></td>
<td>In-direct band gap</td>
<td>In-direct</td>
<td>direct =&gt; LED</td>
</tr>
<tr>
<td>Max. Temp. = 125° C</td>
<td>200° C</td>
<td>250° C</td>
<td></td>
</tr>
<tr>
<td>Breakdown Field = 0.3 MV/cm</td>
<td>2.2 MV/cm</td>
<td>2.6 MV/cm</td>
<td></td>
</tr>
<tr>
<td>6.5 kV IGBT</td>
<td>15 kV MOSFET</td>
<td>20 kV JFET</td>
<td></td>
</tr>
<tr>
<td>400 Hz</td>
<td>4 kHz</td>
<td>6 kHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrons &amp; holes =&gt; Slow Switching</td>
<td>Electrons Only =&gt; Fast Switching</td>
<td>Electrons Only =&gt; Fast Switching</td>
</tr>
</tbody>
</table>

Higher Temperature
Higher Voltage
Higher Frequency

More Efficient
Smaller, Cheaper
Power Electronics
SiC vs. GaN: Both technologies are critical to Power Electronics - in different voltage ranges

• GaN based Power Electronics:
  – Suitable from 200 to 900 V
  – Ideal applications:
    – 0.1 to 10 kW Power Supplies
    – Laptop power adapters
    – Micro and string solar inverters up to 10 kW

• SiC based Power Electronics:
  – Suitable from 900 to 15,000 V
  – Ideal applications:
    – String solar inverters >10 kW
    – Central Solar and Fuel Cell Inverters up to several MW
    – Automotive Inverters and Quick Chargers
    – Traction
    – Medium Voltage Motor Control for Oil and NG high rpm direct drive
    – Distribution Grid Based Power Flow Controllers
Next Generation Power Electronics (WBG) Initiative Strategy

Power America Institute at NC State University
Capture U.S. opportunity for manufacturing leadership in:
Wide Bandgap Power Devices, Power Electronics

- Commercial Foundry
- Advanced Modules
- Power Electronics

Train Graduate Students in using WBG Devices in Power Electronics
Opportunities for SiC Power Electronics for Hydrogen and Fuel Cell Applications

Cree Power – Oct 2014

Jeff Casady, John Palmour, +001.919.308.2280 or jeffrey_casady@cree.com

www.cree.com
Cree SiC Portfolio - > 90 products from 2002-14

DIODES SINCE 2002
>70 products and growing
0650V  2A-50A
1200V  2A-50A
1700V  50A

MOSFETS SINCE 2011
>13 products and growing
1200V  7A-60A
1700V  3A-50A

Power Modules SINCE 2012
>7 products and growing
1200V  20A-300A
1700V  250A

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Cree 1700V, 8mΩ, ½ bridge power module released

Full commercial release – September 2014

Gate drivers, app notes available

First all-SiC power module released commercially @ 1700V

Available globally – Digikey, Mouser, Richardson/Arrow (right), …

2 channel; 1.2/1.7 kV 62 mm module gate driver direct mount
Proven Reliability with Industry-Leading Standards

Cree Field Failure Rate Data since Jan. 2004 through Oct. 2014

<table>
<thead>
<tr>
<th>Product</th>
<th>Device Hours</th>
<th>FIT (fails/billion hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSDxxx60</td>
<td>483,000,000,000,000</td>
<td>0.05</td>
</tr>
<tr>
<td>C2Dxxx120</td>
<td>171,000,000,000,000</td>
<td>0.43</td>
</tr>
<tr>
<td>C3Dxxx60</td>
<td>481,000,000,000,000</td>
<td>0.02</td>
</tr>
<tr>
<td>C4Dxxx120</td>
<td>46,800,000,000,000</td>
<td>0.04</td>
</tr>
<tr>
<td>SiC MOSFET</td>
<td>1,340,000,000,000</td>
<td>3.0</td>
</tr>
<tr>
<td>Total</td>
<td>1,183 Billion</td>
<td>0.099</td>
</tr>
</tbody>
</table>

- 0.08 FIT rate is >10X lower than the typical silicon
- SiC diodes first released in 2001
- SiC MOSFETs first released in 2011
Cost reduction from volume and device refinement

Solid Lines = Actual
Dotted Lines = Projections
Section – Partial Listing of

Existing MOSFET Portfolio Applications
1200V SiC MOSFET design wins in PV inverters

“Through this partnership with Cree and their SiC technology, Sanix is able to capture more market share in the competitive Japan solar market,” says Sanix’s general manager Hiroshi Soga. “Cree’s ... SiC switches reduced losses in our inverter electronics by more than 30% versus the silicon super-junction MOSFETs we were considering…”

PV Inverters
- lower losses, costs
- better performance

1200V, 80mΩ SiC MOSFETs have been selected by Japan’s Sanix Inc.

9.9kW three-phase solar inverters
Higher power density, lower losses

April 2013 press release

Sept 2014 press release
“The drop-in feature of Cree’s new all-SiC power module allows us to achieve 99 percent efficiency while reducing the power module count by a factor of 2.5 in our existing HF induction heating systems,” said John K. Langelid, R&D manager, EFD Induction. “These benefits are greatly valued as a reduced cost of ownership by our end customers.”

Induction Heating power supplies

- 2.5X lower part count
  - better implied reliability
- Reduction in power losses
- Reduced COO

May 2014 press release
1200 V SiC MOSFET win in on-board DC/DC converter

- DC-DC topology with 1200 V SiC MOSFET (C2M0080120D)
- Active clamp forward topology with 750 V DC in / 27 V DC out
- SiC MOSFET enabled:
  - ↑ efficiency from 88% to 96%
  - ↓ size and weight by 25% - 60%
  - ↓ both cost and audible noise
  - Eliminated cooling fans

For HEV/EV bus (Shinry)
1200 V SiC MOSFETs used in 8 kW EV charger demo

1200 V SiC MOSFET (C2M0160120D) enables:

- **Simpler topology, ½ the components,**
- **260 kHz, (> 35W/in³),**
- **Lower system cost, > 98.1% efficient**
- **Not possible to do this in silicon**

---

**Items**

<table>
<thead>
<tr>
<th>3-level FB w/ Si MOS @ <strong>120kHz</strong> resonant freq.</th>
<th>2-level FB w/ SiC MOS @ <strong>260kHz</strong> resonant freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFETs</td>
<td>MOSFETs</td>
</tr>
<tr>
<td>→ 650 V Si SPW47N60CFD in 3 level</td>
<td>→ 1200 V SiC C2M0160120D in 2 level</td>
</tr>
<tr>
<td></td>
<td>16 pcs</td>
</tr>
<tr>
<td>Flying diode</td>
<td>8 pcs</td>
</tr>
<tr>
<td>Resonant Inductor (PQ3535)</td>
<td>None</td>
</tr>
<tr>
<td>Resonant Capacitors</td>
<td>1 pc Lr=15uH</td>
</tr>
<tr>
<td>Magnetize transformer</td>
<td>1 pcs PQ6560 Lm=100 uH</td>
</tr>
<tr>
<td>Resonant Capacitors</td>
<td>35nF</td>
</tr>
<tr>
<td>MOS Drivers</td>
<td>25 nF</td>
</tr>
<tr>
<td>Peak efficiency</td>
<td>4 pcs</td>
</tr>
<tr>
<td></td>
<td>97.8%</td>
</tr>
</tbody>
</table>

**Reference:** J. Liu, “Highly efficient and compact ZVS resonant full bridge converter using 1200V SiC Mosfets,” PCIM 2014

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Benefits of SiC in power electronics are compelling in 10 to 50 kW boost stage

- BOM cost decreases
- Size, weight & losses all decrease
- C2M0080120D compared to H3 IGBT*

<table>
<thead>
<tr>
<th>Size</th>
<th>Weight</th>
<th>BOM</th>
<th>Losses</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kW</td>
<td>50% ↓</td>
<td>40% ↓</td>
<td>10-20% ↓</td>
<td>20% ↓</td>
</tr>
<tr>
<td>50 kW</td>
<td>50% ↓</td>
<td>60% ↓</td>
<td>10-18% ↓</td>
<td>40% ↓</td>
</tr>
</tbody>
</table>

* Reference: J. Liu (PCIM 2013)
Commercial PV installation 100kW – 1 MW

- Decentralized commercial roof top application.
- There is a need for a compact, light weight, high power density, three phase PV string inverter.
- Can lower installation cost and more widespread adoption of solar energy.
- SiC devices enable the best solution to achieve this need.

Power density needed
> 1 kW/Kg
### Kaco Blueplanet 50.0 TL3

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Power MPPT Voltage Range</td>
<td>480 – 850 VDC</td>
</tr>
<tr>
<td>Operating MPPT Voltage Range</td>
<td>200 – 850 VDC</td>
</tr>
<tr>
<td>No. Independent MPPT Input</td>
<td>1</td>
</tr>
<tr>
<td>Nominal output power</td>
<td>50 kW</td>
</tr>
<tr>
<td>CEC Efficiency</td>
<td>97.5%</td>
</tr>
<tr>
<td>Peak Efficiency</td>
<td>N/A</td>
</tr>
<tr>
<td>Power Factor</td>
<td>&gt; 0.99</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>480 Vac</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>-30 °C to 60 °C (de-rated &gt; 45 °C)</td>
</tr>
<tr>
<td>Cooling</td>
<td>Forced convection</td>
</tr>
<tr>
<td>Weight</td>
<td>173 kg</td>
</tr>
<tr>
<td>Isolation Transformer</td>
<td>No</td>
</tr>
<tr>
<td>Volume</td>
<td>840 x 355 x 1360 mm</td>
</tr>
</tbody>
</table>

#### 50 kW, TL3 series

Power density = 0.29 kW/Kg

Need: Increase this value > 3 x

Cree SiC Technology can achieve this…

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## What Can Be Done With Cree SiC Technology

<table>
<thead>
<tr>
<th></th>
<th>3-ph, PV String Inverter</th>
<th>PV String Inverter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full Power MPPT</strong></td>
<td>480 – 850 VDC</td>
<td>450 – 800 VDC</td>
</tr>
<tr>
<td><strong>Operating Voltage</strong></td>
<td>200 – 850 VDC</td>
<td>400 – 950 VDC</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>No. Indep MPPT Input</strong></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Nominal output power</strong></td>
<td>50 kW</td>
<td>50 kW</td>
</tr>
<tr>
<td><strong>CEC Efficiency</strong></td>
<td>97.5%</td>
<td>97.8%</td>
</tr>
<tr>
<td><strong>Peak Efficiency</strong></td>
<td>98.3%</td>
<td>98.7%</td>
</tr>
<tr>
<td><strong>Power Factor</strong></td>
<td>&gt; 0.99</td>
<td>&gt; 0.99</td>
</tr>
<tr>
<td><strong>Output Voltage</strong></td>
<td>480 Vac</td>
<td>480 Vac</td>
</tr>
<tr>
<td><strong>Operating Temperature</strong></td>
<td>-30 °C to 60 °C (de-rated &gt; 45 °C)</td>
<td>-30 °C to 60 °C (no de-rating)</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>Forced air</td>
<td>Forced air</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>173 kg</td>
<td>50 kg</td>
</tr>
<tr>
<td><strong>Isolation Transformer</strong></td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Volume (m³)</strong></td>
<td>0.41</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>840 x 355 x 1360 mm</td>
<td>1000 x 700 x 300 mm</td>
</tr>
</tbody>
</table>

Power Density = 1 kW/Kg
50±kW PV Inverter Design
SiC PV Inverter Reference design Overview

Channel A
Channel B

450 to 800 VDC
2x MPPT channels

MPPT Boost, 75kHz

3-ph Inverter, 48kHz

Control Plane

Aux. Power Supply

Driver

825 VDC

LC line Filter

480 Vac rms l-l

Scalable to any numbers of MPPT channels

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PV String Inverter Schematic

Input Filter

4-ph interleaved Boost Converter

DC Link

3-ph T-Type Inverter

Output Filter

2x C2M0080120D, SiC MOSFET in parallel per phase leg.
2x C4D10120D, SiC MPS diodes in parallel per phase leg.

10x 700uF 600VDC film

2x C2M0025120D, SiC MOSFET in parallel per phase leg upper and lower switch.
1x C2M0025120D, SiC MOSFET per T-leg.
1x C5D50065D, SiC MPS Diode per T-leg.

3x 4uF, 470Vac film
3x 230uH, metglas core
Output Power = 47.8kW
Output Voltage = 492 Vac I-I rms
Output Current = 56A rms
DC link Voltage = 850 VDC
3-phase, balanced resistive load
SiC System Efficiency v/s Si based system*

Better Overall efficiency @ 1/3rd the weight

* Independent test data for KACO BluePlanet 50.0 TL3 provided by gosolarcalifornia.ca.gov
PCB Assembly Of The 50kW Evaluation Unit

Boost Chokes*

EMI Filter Choke

MPPT Ch A

MPPT Ch B

Phase Gate driver

Controller

2pcs C2M0080120D per each phase
## Electrical Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC output voltage</td>
<td>VDC</td>
<td>800</td>
</tr>
<tr>
<td>Max. output power</td>
<td>kW</td>
<td>50</td>
</tr>
<tr>
<td>DC input voltage</td>
<td>VDC</td>
<td>400 – 600</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>97.8 – 99.14</td>
</tr>
<tr>
<td>Switching Frequency / phase</td>
<td>kHz</td>
<td>75</td>
</tr>
<tr>
<td>Operating temp*</td>
<td>ºC</td>
<td>-25 to +35</td>
</tr>
<tr>
<td>Storage temperature range</td>
<td>ºC</td>
<td>-35 to +85</td>
</tr>
<tr>
<td>Isolation voltage</td>
<td>kV</td>
<td>tbd</td>
</tr>
</tbody>
</table>

* Restriction imposed due to limited testing for evaluation products.

* Hardware designed as an evaluation platform and not a qualified product.
50kW, 4 phase Interleaved Boost Converter Features

- 2x devices hard paralleled per phase
- 4 phase interleaved Boost with full SiC devices
- Input voltage: 400V-600Vdc
- Output voltage: 800Vdc
- Output power: 50KW (12.5KW per channel)
- Controller preset
- 2x independent MPPT channels

Diagram showing the circuit with labeled components and connections.
Measured Versus Calculated Efficiency Over Varying Load

Note: Gate to source turn on resistor is 15Ohm and turn off resistor is 5Ohm
Ambient temperature is 25°C with fan cooling

50KW Interleaved Boost Converter with 800V DC Output

Efficiency

Loading (%)
**Thermal Images With 400V In / 800V Out at Full Load**

<table>
<thead>
<tr>
<th>Part</th>
<th>Tc (°C) #1</th>
<th>Tc (°C) #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2M0080120D</td>
<td>92.6</td>
<td>94.4</td>
</tr>
<tr>
<td>C4D10120D</td>
<td>67.5</td>
<td>64.9</td>
</tr>
<tr>
<td>Boost Inductor</td>
<td>69.7</td>
<td></td>
</tr>
</tbody>
</table>

Note: Testing is based on full load operation after 30min with fan to cool system
Ambient temperature = 25°C
50kW Boost Evaluation unit Availability

- Order P/N: **CRD50DD12N**
- Estimated cost per unit: $4,000 USD
- CAD model in STEP format available
- Available now
- Schematic and layout files available

Hardware designed as an evaluation platform and not a qualified product.
3-Phase Inverter
Topology Analysis For 3-Phase Inverter

Power Stage Efficiency vs. Switching Frequency (kHz)

- 2L Si
- 3L-NPC Si
- 3L-T Si
- 2L SiC
- 3L-T SiC

Switching Frequency (kHz)

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Inverter Topology – three level T-type

Main Lower & Upper MOSFET position: 2x Cree 1.2kV SiC Mosfet, 60A, 25 mΩ
Main Diode position: None, uses MOSFET Body diode
T-Branch MOSFET position: 1x Cree 1.2kV SiC Mosfet, 60A, 25 mΩ
T-branch Diode position: 2x Cree 650V, 50A, C3D50065D

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Section –

Future SiC MOSFET products – scaling to medium voltage
SiC amp ratings are much less than Si

- System cost reduction of 20% using 1200V SiC
  - Increased frequency reduces size and weight of magnetics
  - Lower losses reduce system cooling requirements
  - Amperage rating for SiC less than half required for Si IGBTs
SiC voltage ratings are much less than Si?

Si Volts are not SiC Volts

6.5 kV Si IGBT used for 3.6 kV drives (100 cosmic ray FIT rate)

4.5 kV SiC MOSFET used for 3.6 kV line?

10 kV SiC MOSFET used for 7.2 kV?

- Medium Voltage SiC MOSFET roadmap must respond to application
  - 10X higher switching frequency, lower thermal dissipation possible
  - Cosmic ray, other reliability metrics may be 100X better
  - All requirements, eg. short circuit, surge must be understood
Section –

Future Target Applications
Application Market Pull for MV SiC from:

- AC Medium Voltage Drives Applications
- Railway Applications (3.3 kV SiC already being adopted in rail)
- Grid-tied Solar Applications
- HVDC Applications (Off-shore wind, hydro, …)
- Grid-tied Power Distribution (Energy-intensive structures such as factories, data centers)
Advantages of medium voltage DC distribution:
• Flexible subunit power rating from a few kW to > 2 MW
• Smaller, lighter, cheaper power cables with higher voltage
• Eliminate large, heavy, costly transformer
• Reduce number of system components
10 kV SiC MOSFETs in Boost Converter (Fraunhofer ISE)

Efficient, “transformer-less” power distribution to medium voltage grid

- Fraunhofer DC-DC converter used 10kV SiC MOSFETs from Cree
- 30 kW DC voltage converter with 3.5 kV input voltage, 8.5 kV output voltage, 98.5% efficient
- 8kHz switching frequency 15X higher than possible with conventional silicon devices in the same voltage range.
Thank You

amit.talapatra@ee.doe.gov

Presenters: Jeff Casady (Jeffrey_Casady@cree.com) and John Palmour (john_palmour@cree.com) of Cree Inc.

DOE Hosts: Eric Miller (eric.miller@ee.doe.gov) and Anant Agarwal (anant.agarwal@ee.doe.gov)

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