SiC Enabling EV Applications

- SiC State of the Art
- SiC System Impact
- SiC Maturity

Guy Moxey Dec 2018
Adoption of SiC into Various Applications – It’s all around

**PV Inverters**
- Shipping in high volume
- MOSFETs
- Diodes
- Modules

**Battery Chargers for EV**
- Shipping in high volume
- MOSFETs
- Diodes
- Modules

**Server Power Supply**
- Shipping in high volume
- MOSFETs in evaluation
- Diodes shipping in high volume

**Traction**
- Shipping in volume
- SiC Modules
Automotive SiC Has Dramatic Growth Potential...

SiC EV Market

$2.4B
SAM 2022

300x increase

$7M
Worldwide SiC Revenue 2017

Market Influencers

- Within ten years half of all model types manufactured will be EVs
- Policy tailwinds – emission standards are tightening
- Increasing Range
- Decreasing cost

…but ramping semiconductor capacity takes time and significant investment
Why SiC = Highest Efficiency and Power Density

SiC Characteristics

- Lower Resistance
- Higher Frequency
- Higher Operating Temperature

System Benefits

- Smaller Size / Higher Density
- Smaller passive components
- Simpler Cooling

Silicon Carbide vs Silicon

![Graph showing Switching Efficiency and Power Density comparison between SiC and Si](image-url)
What a difference a year makes for Automotive SiC…

Cumulative volume of car companies with SiC-based inverter prototypes for ‘22-’25 launch

As of August 2017

As of August 2018

No Total  Yes Total

No Total  Probable Total  Yes Total
Focused Applications: Automotive

**On-Board Chargers**
- Lower system cost than Si
- 650-900V SiC MOSFETs

**DC/DC Converters**
- Battery voltage to bus voltage
- Up to 100kHz
- Compact, efficient, lightweight

**Drive Train Inverters**
- Lower on-state losses
- Reduce battery and/or increase range

- Improved cost & efficiency
- MOSFETs, Diodes, & Modules
SiC Based On-Board EV Charger (OBC)

What:
• Slow charging from home / garage / office
• 6-8 hrs charge duration

Where:
• PHEV, BEV battery charging 1.6kW, 6.6kW to 22kW
• AC charge from socket to car
• Car then converts AC to DC for on board battery charging

Driving factors:
• Highest efficiency
• Highest power density (small and light weight)
• Future trends bi-directional energy flow

SiC Advantage:
• >1% higher efficiency
• ~30% smaller system size
• Lower system cost
Block Diagram: Bi Directional 6.6kW Silicon Carbide OBC

Totem Pole PFC  DC:390V-680V

Bi-Directional DC/DC

Battery 250V-450V

CLLC Resonant Tank

AC

8 devices  4 devices  4 devices

2 devices in parallel for PFC, single device for DC/DC
Uses C3M SiC MOSFET in high performance TO-247-4L package with Kelvin source
Peak System Efficiency >96%

SiCMOSFET
C3M0065100K
TO-247-4 Package
SiC: Highest Power Density = Space Savings in the Vehicle

**SiC Characteristics**
- Lower losses
- Higher Frequency
- Higher Efficiency

**System Benefits**
- Smaller Size / Higher Density
- Smaller passive components
- Simpler / smaller Cooling

- 6.1kW On Board Charger (OBC) is 4x higher power density than existing 3.3kW
EV Drivetrain

What:
- 90-350kW+ motor drive inverter
- Single, dual or in hub drives

Where:
- BEV powertrain
- BEV commercial vehicles

Driving factors:
- Vehicle range extension
- Battery cost reduction
- System cost reduction
- Bi-directional energy flow for regen breaking

SiC Advantage:
- ~80% lower drive loss
- ~30% smaller system size
- Lower system cost

Wolfspeed SiC enables smaller batteries and longer driving range with smaller, cooler and lighter systems
Future electric propulsion will be more efficient

The Technical Superiority of High Efficiency SiC Converters

• “Futureproof” – Viper package used to package Wolfspeed SiC MOSFET switches
• Lower switching losses than IGBT technology
• Inverter level testing shows lower losses
• Implication: more vehicle range from a given battery pack capacity

DELPHI

Inverter-level Loss Comparison: 650V Rated Silicon vs. Silicon Carbide
(same voltage and switching frequency)

Silicon (baseline – set to 100%)

Silicon Carbide

Total Inverter Losses [%]

Phase Current [Amps rms]

0 50 100 150 200 250 300 350 400 450

29% 35% 45% 59%
SiC higher efficiency - key to inverter loss reduction

- Si IGBT and Wolfspeed SiC MOSFET compared for traction drive operation
- Synchronous rectification for SiC devices, no added parallel diodes
- Compared to Si, SiC reduces inverter losses by ~78% in electric-only drive mode for EPA metro-highway cycle

Enables 7-10% further range for same battery size OR
7-10% reduction in battery capability for same range
SiC MOSFETs Enable EV Drivetrains

- Highest current in industry enabled by close coupling with in-house materials quality and device design
- All Die designed and optimized for drivetrain
- “Drivetrain Menu” for in house, module house, Tier 1 or vertical OEM usage

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<th>1200 V</th>
<th>900 V</th>
<th>650 V</th>
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<tr>
<td>650 V</td>
<td>100A</td>
<td>-</td>
<td>140A</td>
</tr>
</tbody>
</table>

**Key features:**

- Interoperable for Discrete, module or custom footprint packaging
- Selectable for optimized die attach
- Selectable for layout
- 3 voltage nodes align to battery technology selection
Wolfspeed 1200V, 13mOhm SiC MOSFET Die in ABB Power Module

Reliable interconnection technologies for high-performance operation of SiC MOSFETs
Fabian Mohn, ABB Switzerland, Ltd., Corporate Research, Switzerland, fabian.mohn@ch.abb.com
Chuniel Liu, ABB Switzerland, Ltd., Corporate Research, Switzerland, chuniel.liu@ch.abb.com
Jurgen Schuderer, ABB Switzerland, Ltd., Corporate Research, Switzerland, juergen.schuderer@ch.abb.com

Nuremberg, 16 – 18 May 2017

- Cu plate sintered to top of die using Ag sintering at 250°C, with pressure
- Wirebonds connect Cu plate (far right top and bottom) using so-called bond buffer technology
- Sintered Ag clip connection to source (left)
- 1000 cycle thermal shock passed successfully (-40 to +150°C)
- 50um Cu sheet
- More results in manuscript
**What**: Fast charging from charge stations. 30 min charge duration
Bypasses OBC for rapid direct battery charging

**Where**: PHEV, BEV battery charging 80kW – 150kW. DC charge from station to car.
Typically constructed from multiple 15-20kW blocks

**Driving factors**: Highest efficiency, Power density (smaller stations).
Future trends bi-directional energy flow

**SiC Advantage**: >2% higher efficiency, 33% increase in power density
lower system cost
High Power 20kW AC/DC Converter for Off-board Charger

SiC enables high efficiency high power density bi-directional 3 phase AC/DC converter

Simplify with SiC

- Less components
- Lower cost
- Higher efficiency
- Smaller size
- Bi-Directional power

Si MOSFET

Si IGBT

20kW AC-DC power stage

12 Devices

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SiC based 2-level high frequency LLC Resonant Converter

Silicon solution

SiC Solution

Simplify with SiC

15kW Silicon hardware

20kW Silicon Carbide hardware

- 33% more power in 33% less space
- Simplify circuit design
- Lower cost
- Increase Efficiency
- Reduce size
Wolfspeed Qual and Reliability Proving SiC Maturity

- SiC power devices have some unique reliability considerations in addition to Si power devices
- Reliability assessments need to be holistic, comprehensive and specific
- The SiC failure mechanisms have been identified and testing methods have been developed
- Successful product qualifications and field reliability show that the reliability science is paying off, and SiC is ready for large volume manufacturing for high reliability applications
- Industry-wide reliability guidelines and standards are being actively developed

Measured distribution $V_{BRDSS}$ over temp

Rugged Voltage Ratings

1M hrs Vds Lifetime

10M hrs Vgs Lifetime

900V rated voltage
Power Field Failure Rate – 5.4 Trillion hrs - May 2018

<table>
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<tr>
<th>Technology</th>
<th>Fielded Device Hours (Billions)*</th>
<th>FIT Rate (valid field failures per billion device hours)**</th>
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<td>C2M MOSFET</td>
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<tr>
<td>C3M MOSFET</td>
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<td>4.1</td>
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*Calculated today’s date minus confirmed ship date minus 90 days (allowing for time to put into service) * 12 hours per day

**Calculated as: 2 times the number of valid field failures (excludes engineering evaluations, as-received visual defect escapes or issues, as-received test escapes, packaging and assembly quality issues) divided by fielded device hours; includes an additional factor for statistical confidence margin
Automotive Customers need Automotive Products

E-Series Automotive MOSFET is far more than just a qualification :-

• E-Series products are tested to more rigorous AEC-Q101 Automotive qualification test conditions and are the only products PPAP capable.
• E-Series products have a different production test methodology with tighter production test limits.
• E-Series products are assembled on separate Automotive certified package assembly lines with certified operators.
• E-Series products have stricter production controls such as only one lot is allowed per package date code for better traceability.
• Finally, the products can have thicker passivation and thermal performance to ensure they can pass High Temperature, High Humidity and High Voltage test conditions. (THB-80)
SiC Vehicle Electrification – Drivetrain, On Board and Off Board

**The Market Situation**
- Monumental 20 year + new open field opportunity for power
- SiC value is very well understood and accepted
- Multiple approaches to system solution – especially drivetrain
- All OEM’s seeking differentiation & Differing regional approaches

**Driving Factors**
- Increased Power density
- Higher system efficiency
- Range extension
- Lower System cost

**Supplier Imperatives**
- Proven reliability
- Enough capacity
- Product flexibility
- Technology innovation to satisfy future developments
- Component differentiation to allow system differentiation

*A Samples and B samples are being developed NOW*

*The future is electric – and it starts with Wolfspeed*