Silicon Carbide Materials and Devices for Power Switching Applications

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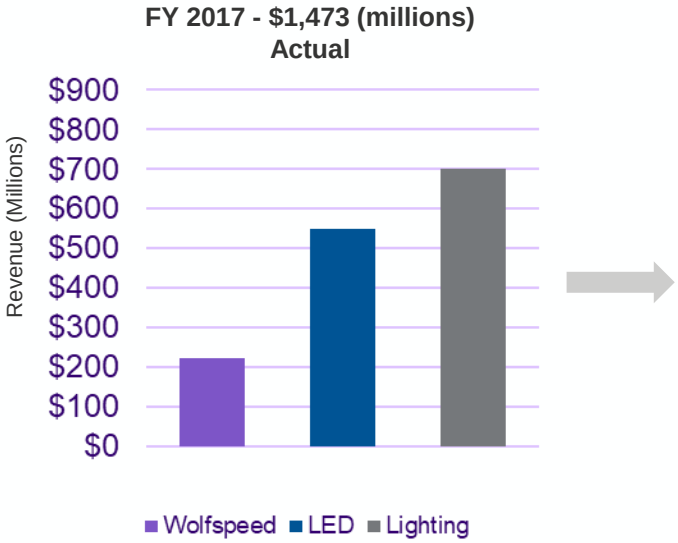
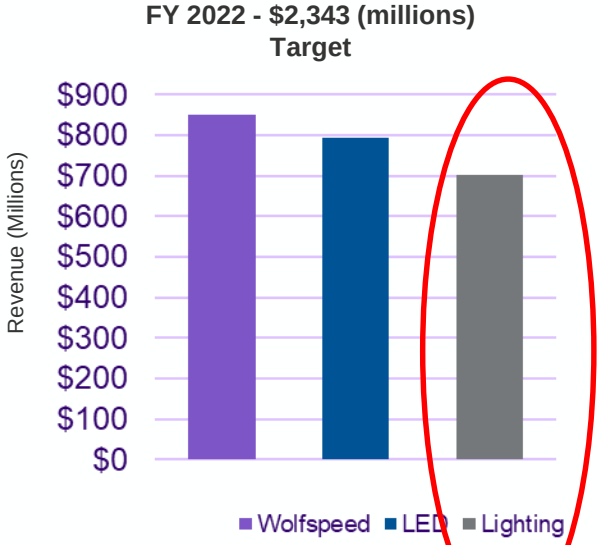
SEMICON® CHINA

Wide Bandgap Technology (SiC and GaN) Changes Everything

Cree's Transformation – Wide Bandgap Semiconductors Leading the Way

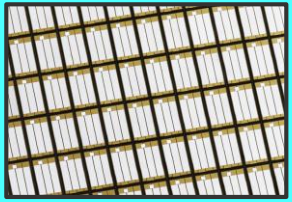




Cree announced intent to sell the Lighting Division to IDEAL Industries

Wolfspeed – Vertically Integrated Manufacturing

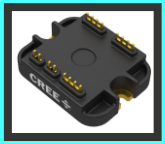
Starting SiC Wafer (100mm or 150mm) → Grow Epitaxial Layer (SiC or GaN) → Fabricate Devices in Wafer Fab



SiC MOSFETs

GaN-on-SiC MMICs

Electrical Test & Saw into Chips → Final Assembly (Pkg. or Module)



Leadership in Power and RF Materials and Devices

SiC Power - #1 Market share*

5+ TRILLION FIELD HOURS
Failure-in-time rates lower than Si

FIRST COMMERCIAL SiC MOSFET
Millions of SiC MOSFETs sold

THOUSANDS OF CUSTOMERS
Servicing all major markets

INDUSTRY'S BROADEST PORTFOLIO
More parts. More packages. More voltages.

GaN RF - #2 Market share*

170+ BILLION FIELD HOURS
Failure-in-time rates lower than Si

MORE THAN 10 YEARS
of commercial GaN HEMT production experience

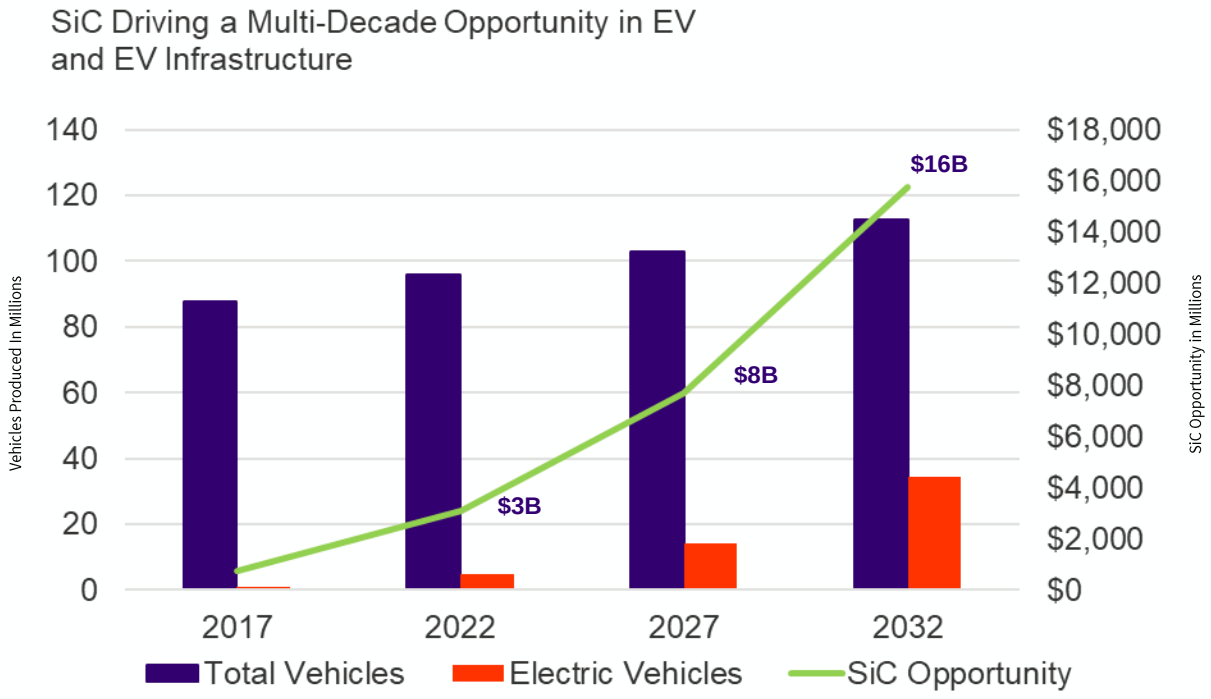
OVER 15 MILLION
devices successfully fielded to date

OPEN FOUNDRY FOR GaN MMICs
excellent PDK ensures first pass success

SiC and GaN Materials - #1 Market share*

*Source: YOLE

Even Modest EV Adoption Drives Significant Opportunity



*Source: Morgan Stanley and Cree Estimates

GaN RF – Enabling Faster 4G and the Transition to 5G

GaN Advantages

- Wider Bandwidth: supports 10X faster download speeds
- Higher Frequency: compact active antennas for real-time adaptable coverage – no more moving in and out of range
- Higher Efficiency: smaller, more energy-efficient systems

- Expanding 4G system capability
- Enabling the 5G revolution

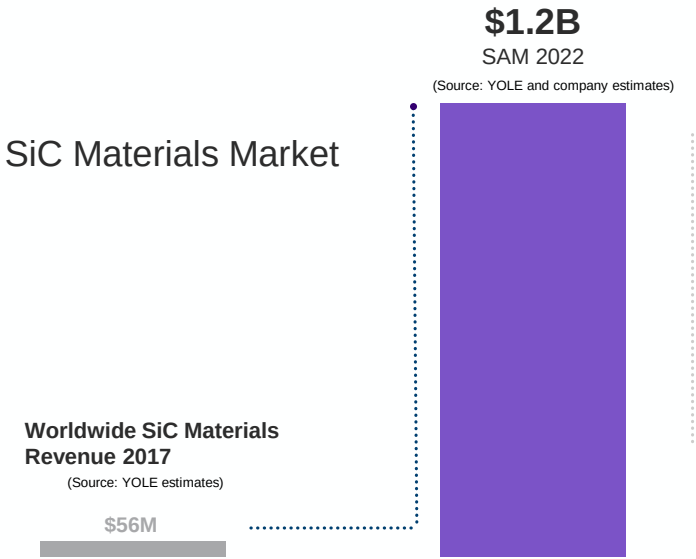
And There's More…

- Grid Modernization
- Motor Drives
- Energy Storage
- Industrial Power
- Fast Charging
- Wind
- And more…

Wolfspeed Materials

A fully integrated materials supplier with the largest and most diverse portfolio, serving a global customer base

SiC Materials Market Expanding To >$1B by 2022



Drivers

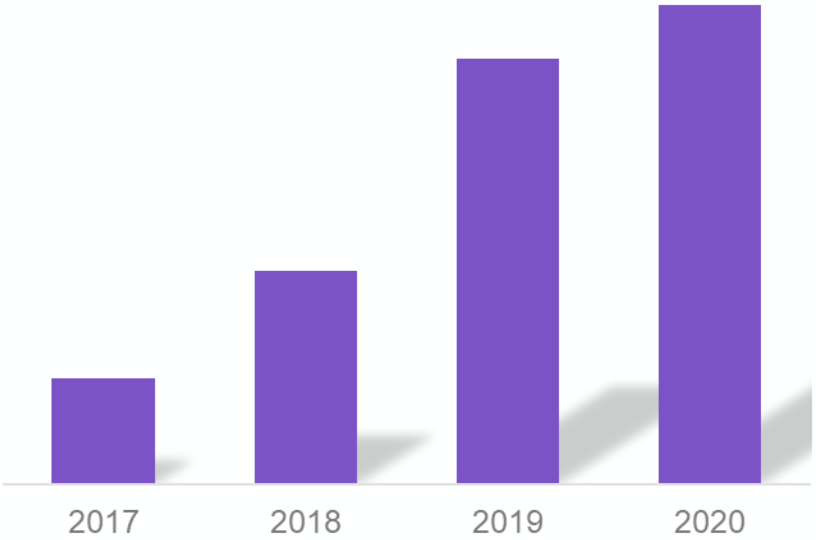
Value proposition for SiC validated in applications that are driving significant growth

- EV applications driving significant volume steps in power wafer market
- Significant adoption in broad industrial market applications
- Telecom/5G commercial growth with major RF players

Leadership in SiC and GaN-on SiC Materials

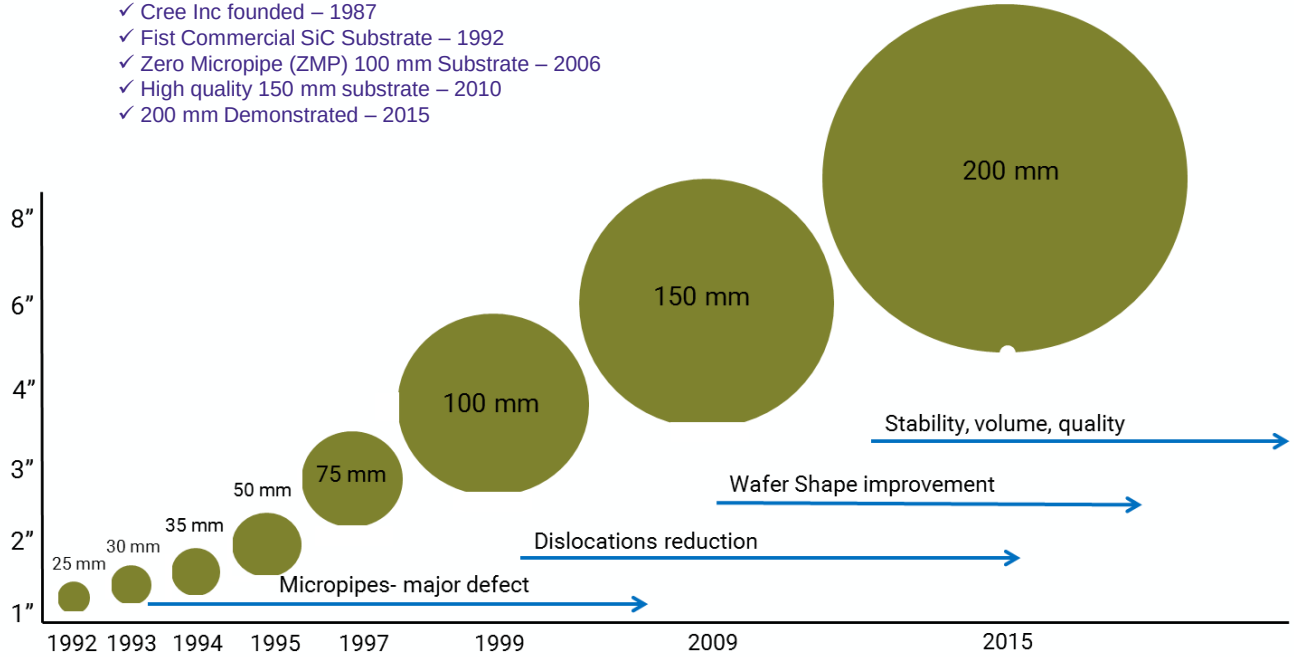
- #1 supply position at major power and RF semi companies globally
- Over three decades of global technology leadership
- Continued innovation through device performance feedback
- Unrivaled scale; significantly ramping capacity to meet demand

Building Capacity



SiC Evolution and R&D Milestones at Wolfspeed

- ✓ Tairov and Tsvetkov – 1978
- ✓ Cree Inc founded – 1987
- ✓ Fist Commercial SiC Substrate – 1992
- ✓ Zero Micropipe (ZMP) 100 mm Substrate – 2006
- ✓ High quality 150 mm substrate – 2010
- ✓ 200 mm Demonstrated – 2015



Most Diverse Materials Product Portfolio

4H-SiC Substrates

- n-type, Semi-Insulating
- 100mm , 150mm, & 200mm (Development)
- High Quality Production Grade

SiC Epitaxy

- n-type & p-type
- S-face or C-face
- 200+ µm

III-Nitride Epitaxy

- GaN/AlGaN /AlInN
- HEMT Structures

Publicly Announced Long Term Agreements with Market Leaders

- February 2018; Cree, Inc. Announces Long-Term Silicon Carbide Wafer Supply Agreement with Infineon;
  - Agreement value > $100M; 150mm Power Substrates & Epi
- October 2018; Cree, Inc. Announces Long-Term Silicon Carbide Wafer Supply Agreement with a Leading Global Semiconductor Company;
  - Agreement value > $85M; 150mm Power Substrates & Epi
- January, 2019; Cree and STMicroelectronics Announce Multi-Year Silicon Carbide Wafer Supply Agreement;
  - Agreement value > $250M; 150mm Power Substrates & Epi

Adoption of SiC into Various Power 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

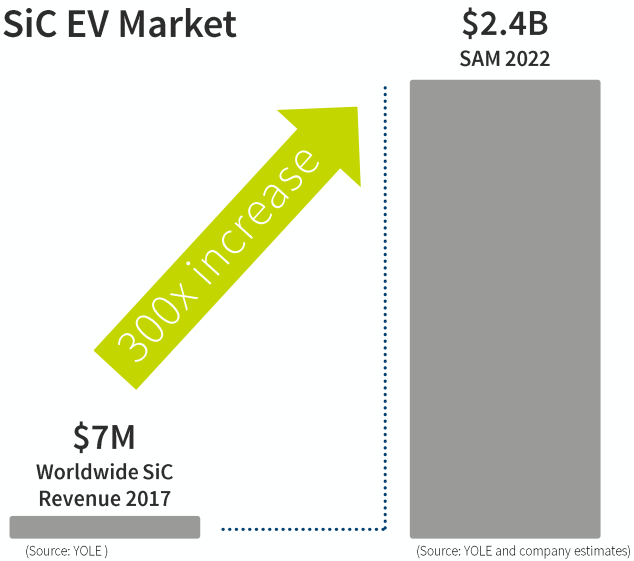
Traction

Shipping in volume

- SiC Modules

SiC Enabling EV Applications

Automotive SiC Has Dramatic Growth Potential…

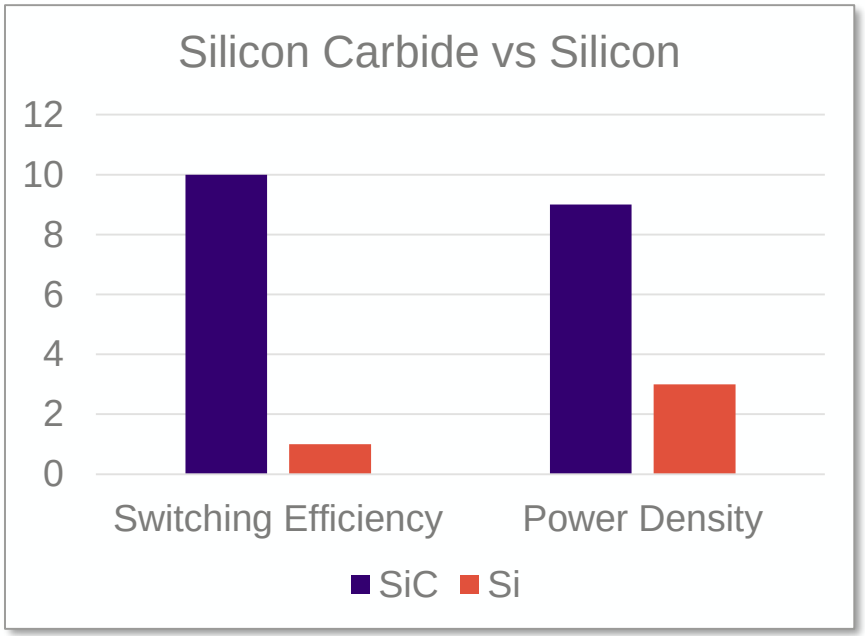


Market Influencers

- 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



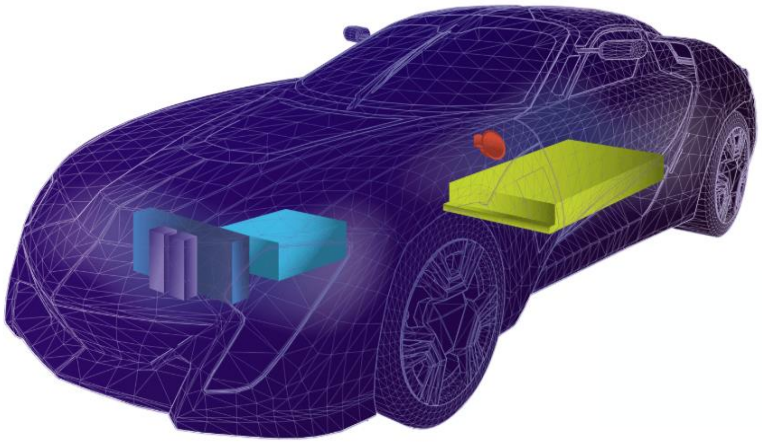
SiC Characteristics

- Lower Resistance
- Higher Frequency
- Higher Operating Temperature

System Benefits

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

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

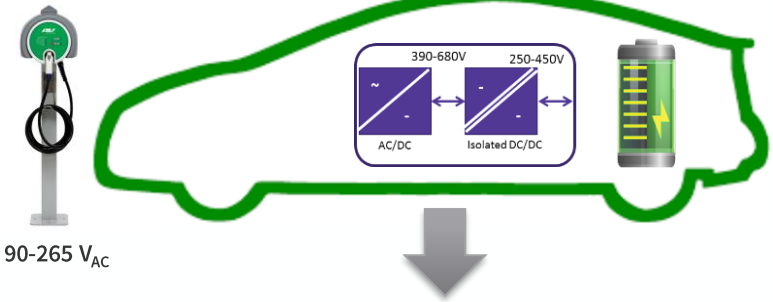
Drive Train Inverters
- Lower on-state losses
- Reduce battery and/or increase range

Off-Board Chargers
- 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 converts AC to DC for on-board battery charging



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

SiC Advantage :
- >1% higher efficiency
- ~30% smaller system size
- Lower system cost

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

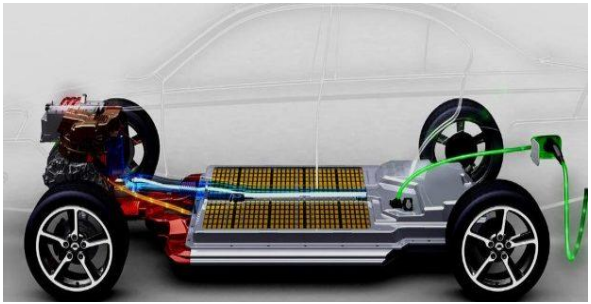
What :
- 90-350kW+ motor drive inverter
- Single, dual or in hub drives

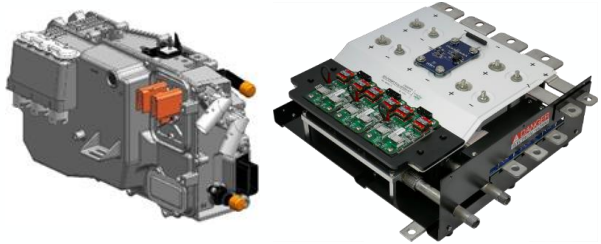
Where :
- BEV powertrain
- BEV commercial vehicles

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

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



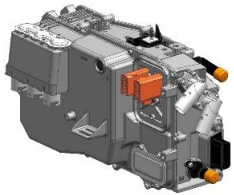


Future electric propulsion will be more efficient

The Technical Superiority of High Efficiency SiC Converters

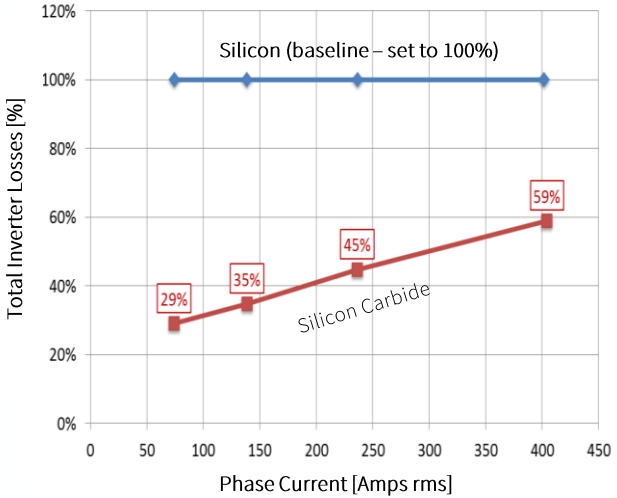
- “Futureproof” – Viper package used to package Wolfspeed SiC MOSFET switches
- Lower switching losses than IGBT technology
- Inverter level testing shows lower losses
- Implication: more vehicle range from a given battery pack capacity

DELPHI



Inverter-level Loss Comparison: 650V Rated Silicon vs. Silicon Carbide

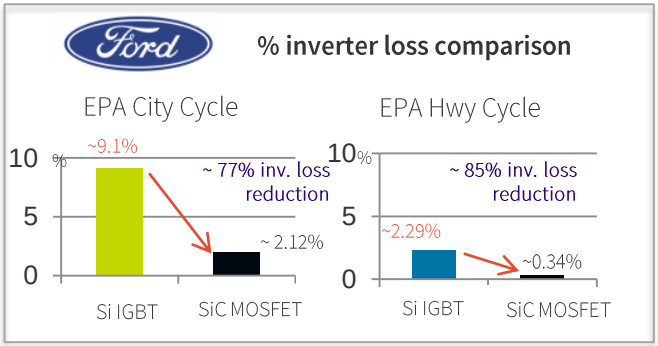
(same voltage and switching frequency)



SiC higher efficiency - key to inverter loss reduction

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Ref. M. Su, et al, WiPDA 2016
Acknowledgment -- EE0006920 “88 Kilowatt Automotive Inverter with New 900 Volt Silicon Carbide MOSFET Technology”

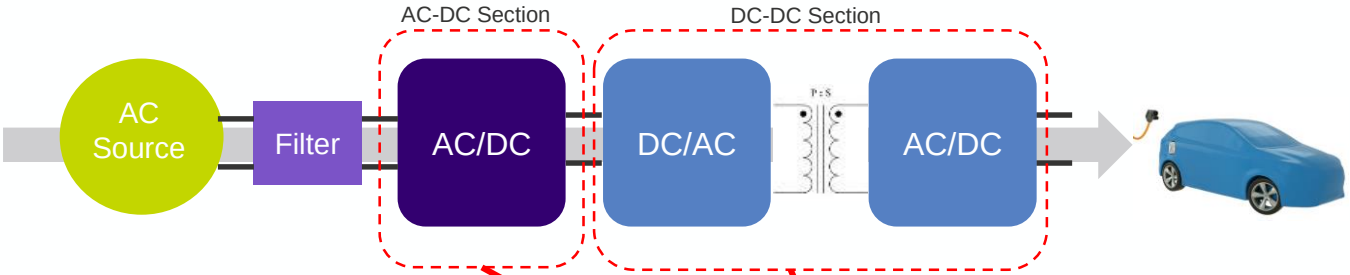


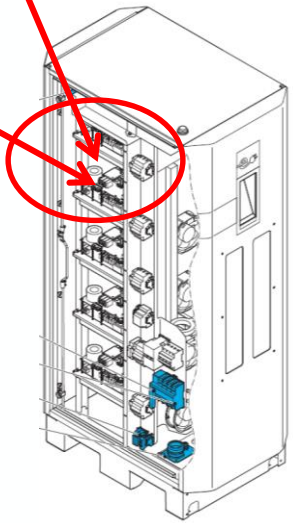
90 kW electric motor used for evaluation

- 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

EV fast off board charger systems – chargers for fast charge stations

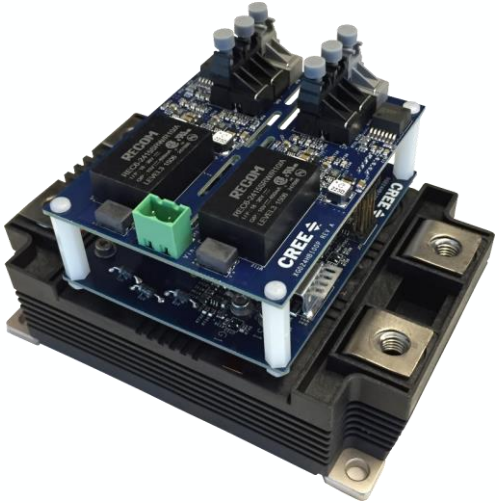


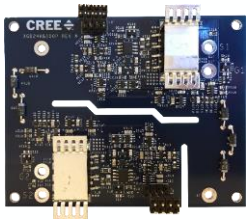


- **What** : Fast charging from charge stations. 30 min charge duration. Bypasses OBC for rapid direct battery charging
- **Where** : PHEV, BEV battery charging 80kW – 150kW. DC charge from station to car. Typically constructed from multiple 15-20kW blocks
- **Driving factors** : Highest efficiency, Power density (smaller stations). Future trends bi-directional energy flow

- **SiC Advantage** : >2% higher efficiency, 33% increase in power density lower system cost

XHV-7 (3.3 kV) Series Power Module Platform

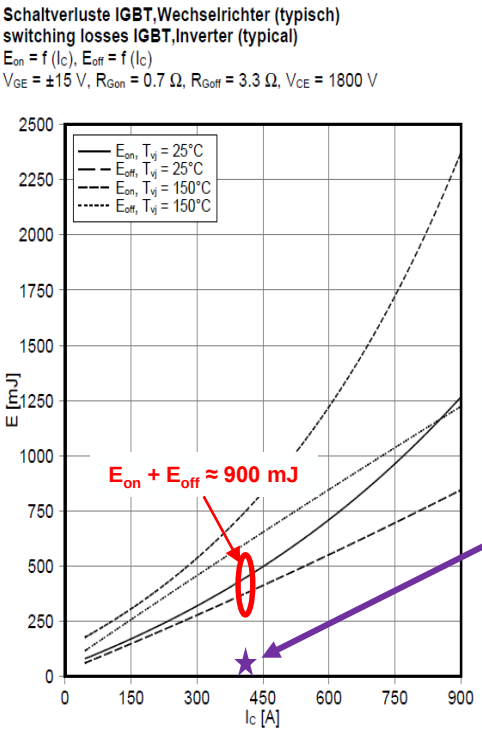




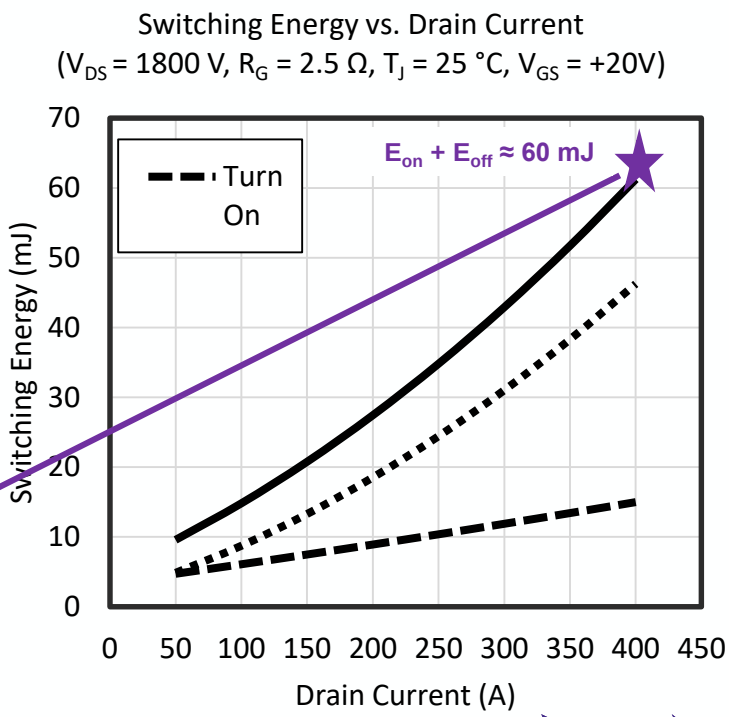
- 3.3 kV, 400 A
- f_{sw} > 50 kHz
- Low inductance ~ 19 nH
- Optical isolation driver, 6 W per channel
- Overcurrent protection, under voltage lockout

XHV-7 Switching Energy Comparison

Infineon 3.3 kV FF450R33TE3



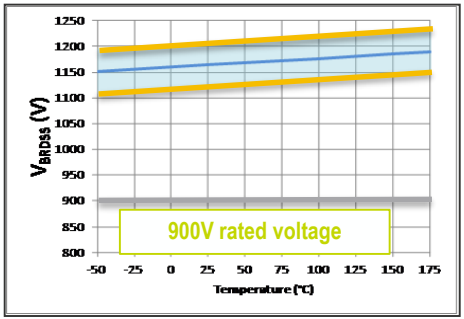
Wolfspeed 3.3 kV XHV-7



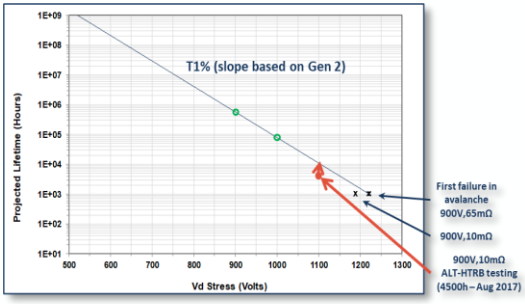
Wolfspeed Qual and Reliability Proving SiC Maturity

- SiC power devices have unique reliability considerations vs Silicon
- Reliability assessments need to be comprehensive and specific
- SiC failure mechanisms have been identified and testing methods 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

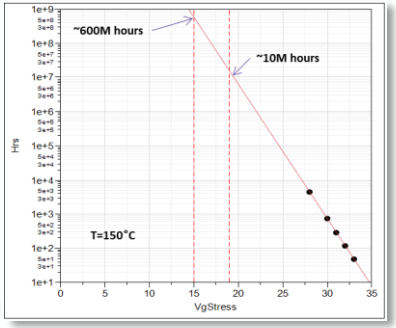
Measured distribution V_{BRDSS} over temp



Rugged Voltage Ratings



1M hrs V_{ds} Lifetime



10M hrs V_{gs} Lifetime

Summary - SiC Market Expanding Rapidly!

150 mm SiC substrates have become the norm for the burgeoning SiC Power Market

- Wolfspeed is the leading SiC material supplier in the world
- >$450M announced in long term supply agreements to other SiC device companies
- 200 mm substrates demonstrated, and the market will migrate to that diameter as the market grows even larger

SiC Power MOSFETs are being accepted in numerous applications

- Solar inverters, Industrial power supplies, and EV chargers
- The reliability of SiC MOSFETs has been proven out and demonstrated in the field
- >6 trillion hours collected for SiC power devices with low FIT rates

The EV market will cause a rapid expansion in this market due to the benefits SiC brings

- Smaller, lighter, more efficient chargers
- Longer range for given battery charge from 7-10% inverter efficiency improvement
- Will help drive EV adoption
- Higher voltage (3.3 kV) devcies coming for train markets

The future is electric – and it starts with Wolfspeed

Powering More. Consuming Less.™