Design and Implementation of SiC In Future Electrical Vehicle and Power System

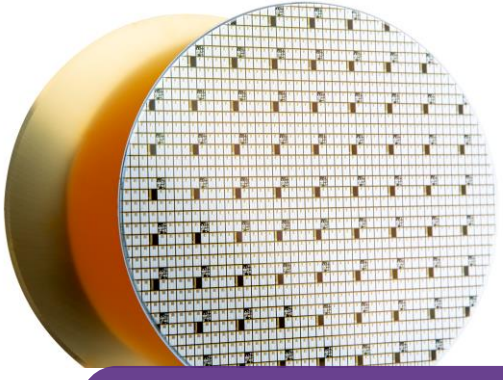
Wolfspeed 2023

AGENDA

- Wolfspeed New 200mm FAB
- Market adoption of Silicon Carbide
- Electric Vehicle Charger Market Summary
- Topology selection and reference design
- Wolfspeed new product/portfolio
- Supporting tools

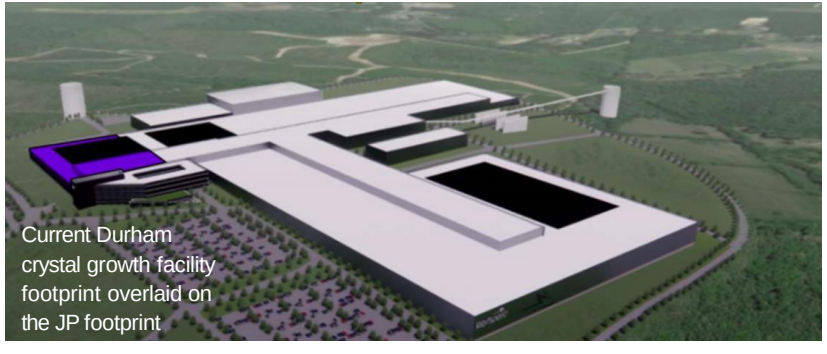
MOHAWK VALLEY FAB:

FIRST, LARGEST, AND ONLY 200 MM SILICON CARBIDE WAFER FABRICATION FACILITY



The fab's 200mm Silicon Carbide wafers are revolutionizing the semiconductor industry, allowing for greater power and efficiency, and leading the way to a more sustainable future.

THE JP FAB – WORLD'S LARGEST SILICON CARBIDE CRYSTAL GROWTH FACILITY



Current Durham crystal growth facility footprint overlaid on the JP footprint

Wolfspeed Durham: currently the world's largest Silicon Carbide crystal growth facility

Key JP Fab Takeaways

- Site in excess of 400 acres; using 250 acres
- Between 1.5M-1.7M sq ft in the first phase
- Greater than 10x the current manufacturing capacity of the Durham facility
- This facility will be highly automated with an enhanced level of robotic processing, balanced with worker amenities

BUILDING LARGEST, STATE OF THE ART, AUTOMATED 200MM SILICON CARBIDE FOOTPRINT TO BEST SERVE INDUSTRY'S TOP CUSTOMERS

The JP Fab

- **10x** increase in Crystal Growth capacity at scale
- 200mm Wafers
- Highly automated

Mohawk Valley

- 200mm Wafers
- Highly automated

Planned Saarland Germany Fab

- 200mm Wafers
- Highly automated

Investing $6.5B

WOLFSPEED IS THE LEADING PURE PLAY, VERTICALLY INTEGRATED SILICON CARBIDE COMPANY

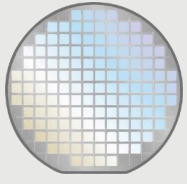
Materials

Devices

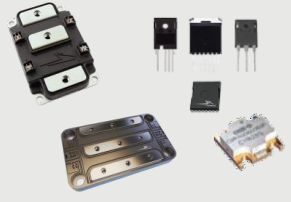
Silicon Carbide Crystals

Wafers and Epitaxy

Wafer Fabrication (Bare Die)



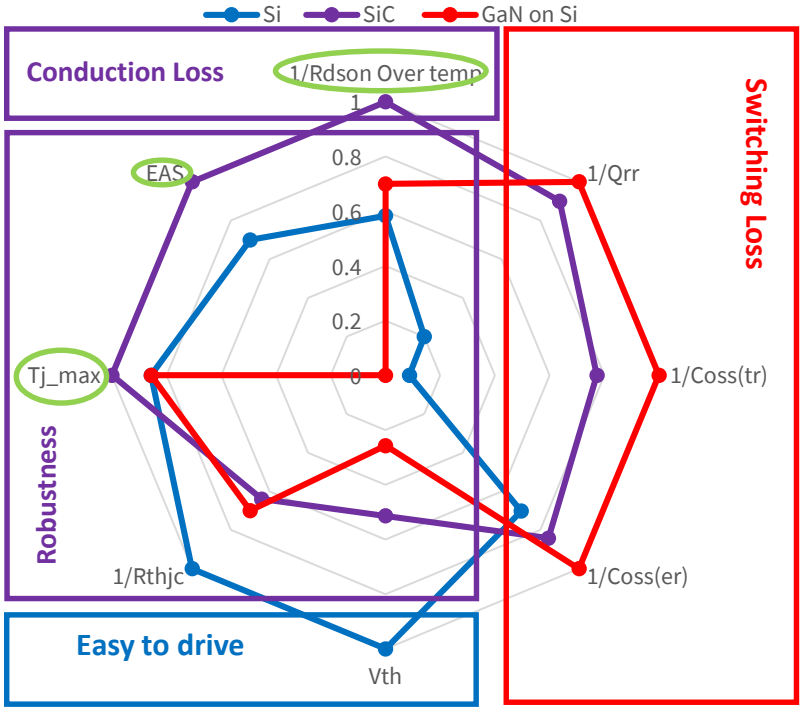
Packaged Parts (MOSFETs, Diodes, Modules, GaN HEMTs, MMICs)



Wolfspeed sells SiC wafers and devices

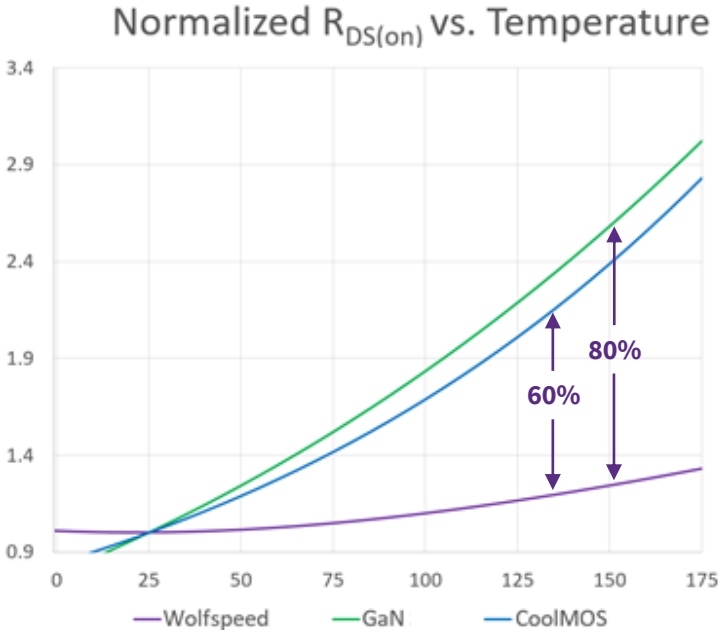
Wolfspeed's vertical integration and 30+ years of experience provide significant competitive advantage

KEY PARAMETERS COMPARISON SI VS. SIC VS. GAN



- **SiC** excels in high voltage, high power and high temperature applications. Low conduction losses boost total efficiency
- **GaN** has the best switching loss performance although total efficiency may suffer due to conduction losses
- **Si** is well understood, easy to drive and suitable for less demanding applications

GAN VS SIC : RDSON AND JUNCTION TEMPERATURE VARIATION



A decent *generic* chart shown typical MOSFET Rdson change over temperature

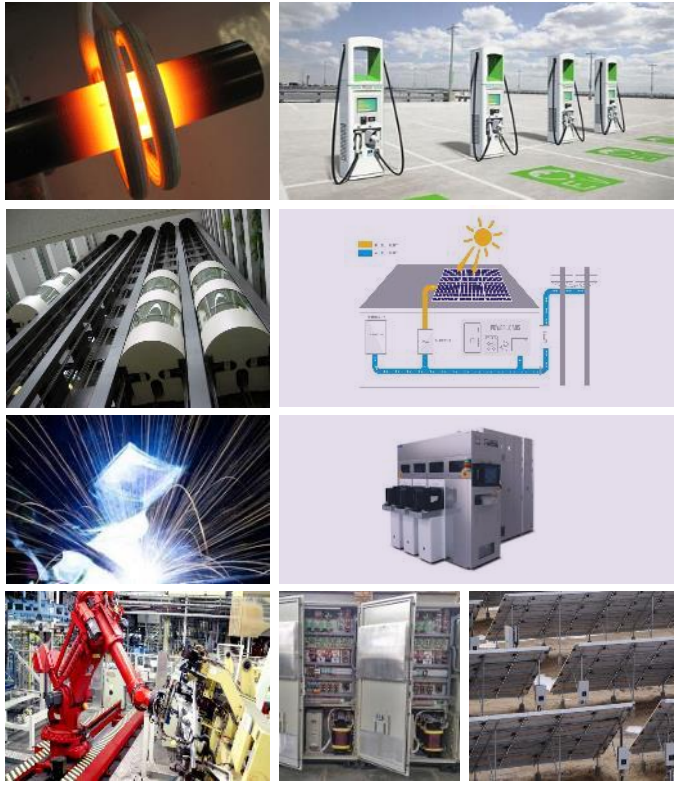
While data sheets show Rdson at 25C, designers have to use Rdson at real junction temperatures – 120C to 140C

Example:
40mO Si or GaN device could be >80mO hot
60mO SiC device will be 80mO hot

Rdson correlates to I^2R loss which is CONDUCTION LOSS
So our 60mO is an equivalent to 40mO for Si and GaN

MARKET ADOPTION OF SILICON CARBIDE

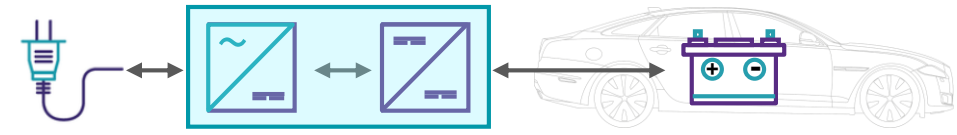
- ✓ **Electrical Vehicle (EV) FAST Charging/OBC/Traction inverter**
  - Where : >3.3KW PFC, DC-DC, DC-AC
  - Why : Integration(all in one), Driver mileage, High efficiency
- ✓ **PV String Inverters**
  - Where : 30kW and higher MPPT booster and inverter
  - Why : Power density, system efficiency, system weight
- ✓ **Energy Storage System**
  - Where : 25kW and higher PFC, charging, DC-DC
  - Why : Power density, system efficiency and scalability
- ✓ **Offline Switch Mode Power Supply**
  - Where : >1KW PFC, DC-DC for server and data center
  - Why : Thermal performance, Power density, system efficiency
- ✓ **Industrial Motor and Motion**
  - Where : >1kW motor drive inverters, embedded driver
  - Why : Small size, High integration, Immunity



Topology selection and reference design

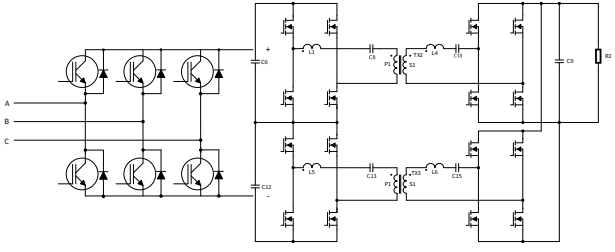
Wolfspeed

FULL SYSTEM SILICON VS. SILICON CARBIDE IN 22kW BI-DIRECTIONAL DC FAST CHARGERS



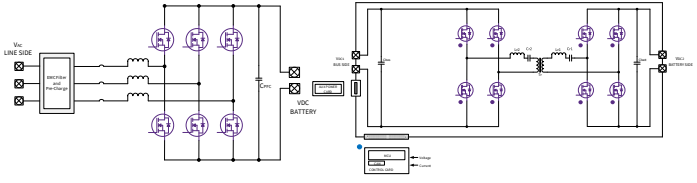
Silicon Design

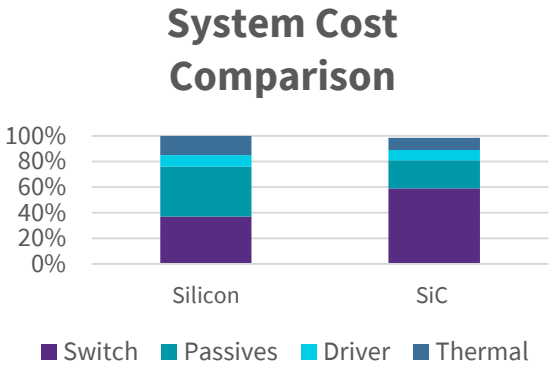
- Peak efficiency 94.8%
- Slower switching frequency (20kHz-100kHz)
- 2.35 kW/L power density



Wolfspeed Full SiC Design

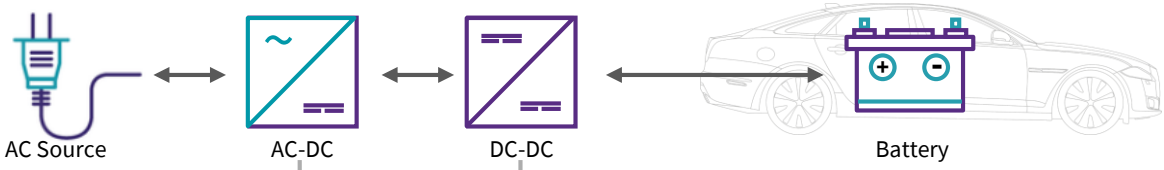
- Peak efficiencies of 97.0%
- Faster switching frequency (45-250kHz)
- 3.55 kW/L power density





Wolfspeed reduces losses by 42% with 51% greater power density at lower system costs

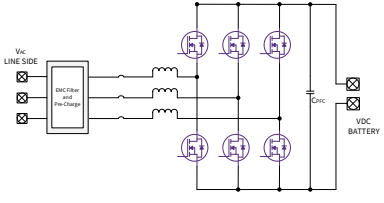
OFF BOARD DC POWER SYSTEM ARCHITECTURE AND ANALYSIS



22kW AC/DC SiC Active Front End

3 Phase bi-directional AFE using 1200V SiC MOSFETs for 800V Battery

- 800V DC Link
- 45kHz operating frequency
- Peak efficiencies of 98.5%
- Power density of >4.6kW/L
- THD <5%
- PF > 0.99

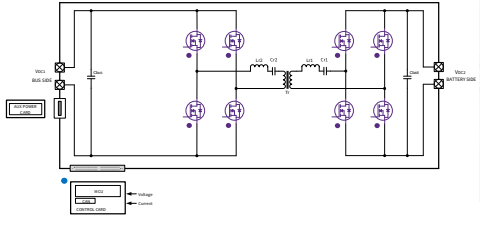


https://www.wolfspeed.com/crd-22ad12n

22kW SiC DC/DC

Full bridge CLLC topology using 1200V SiC MOSFETs for 800V Battery

- 135-250kHz High operating frequency
- Peak Efficiencies of 98.5%
- Power Density of 8kW/L
- Flexible output voltage



https://www.wolfspeed.com/crd-22dd12n

22kW HIGH EFFICIENCY BI-DIRECTIONAL AC-DC CONVERTER [CRD22AD12N]

Features

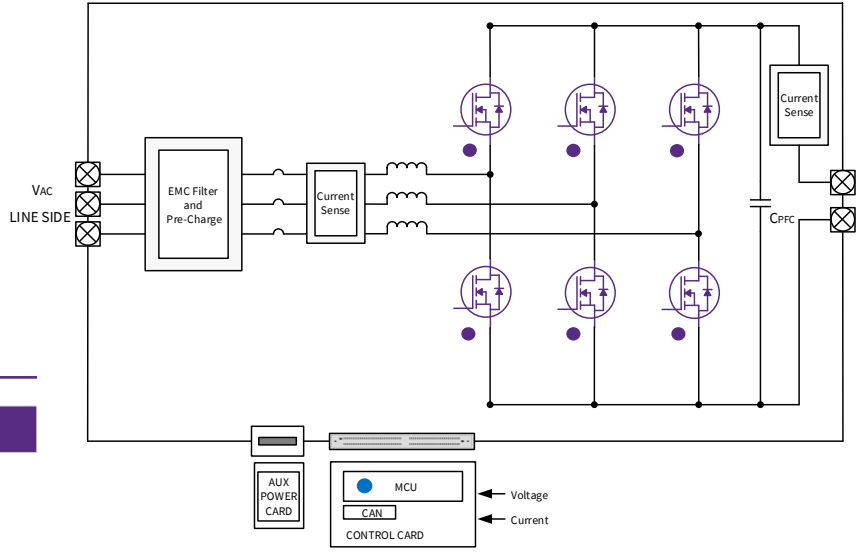
Topology	Three Phase Active Rectifier
Input Voltage	3-Phase AC Input : 304V AC-456V AC 1-Phase AC Input : 180V AC -264V AC
Output	650VDC – 800V DC
Power	22kW
Direction	Bidirectional
Peak Efficiency	>98.5%
Frequency	45 kHz
SiC MOSFET's	6x C3M0032120K - Discretes
Control Scheme	SVPWM (Space Vector Modulated)
Inductor	3x 280uH

Key benefit: High power density and low-cost solution

pcim Europe
Best Paper Award
FINALIST

Tools & Resources

- Design Files: Schematics, BOM and BOM Analysis, Design Files
- Firmware on request



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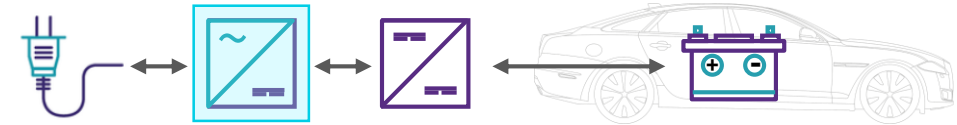
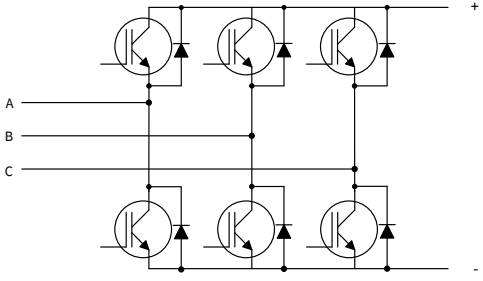
AC-DC IGBT VS. SILICON CARBIDE IN 22kW DC FAST CHARGERS

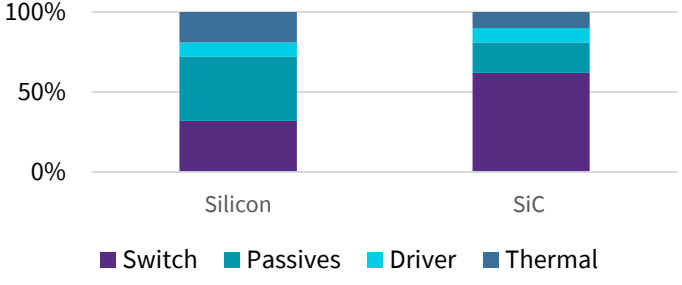


Silicon IGBT Design

- IGBT 20kHz
- Power density 3.5kW/L
- Peak efficiency 97.2%

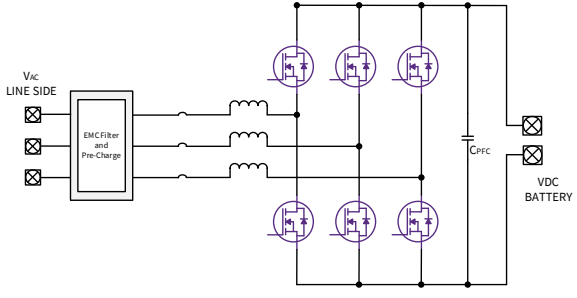


System Cost Comparison



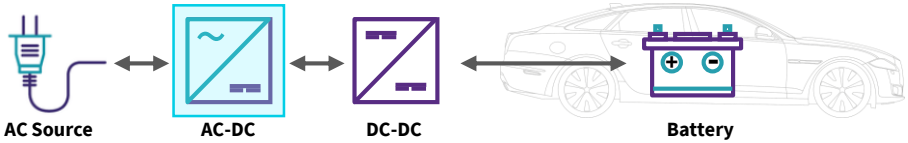
Wolfspeed Full SiC Design

- SiC MOSFET 45kHz
- Power density of >4.6kW/L
- Peak efficiencies of 98.5%

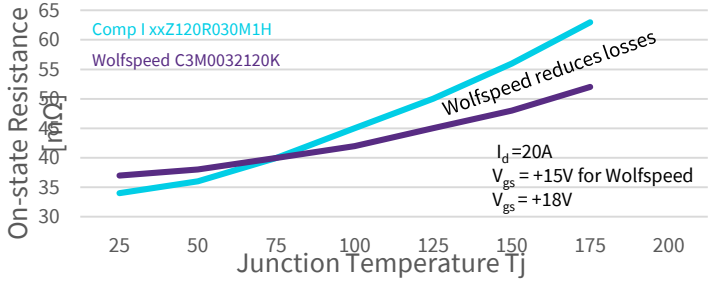


Wolfspeed Silicon Carbide enables 46% less losses for the same costs

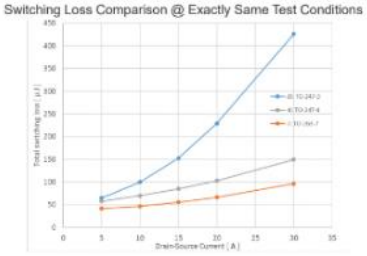
MOSFET SELECTION FOR AC-DC CONVERTER



- SiC MOSFETs increase Rdson much less over temp allowing use of a smaller rated SiC device



- Hard switched, high current, High frequency operation
  - Favor packages with low inductance and Kelvin Pin connections

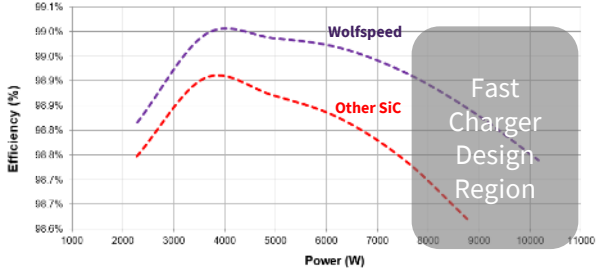


TO-247-3
NO-Kelvin Pin 2.6mm
Creepage 8nH
Inductance

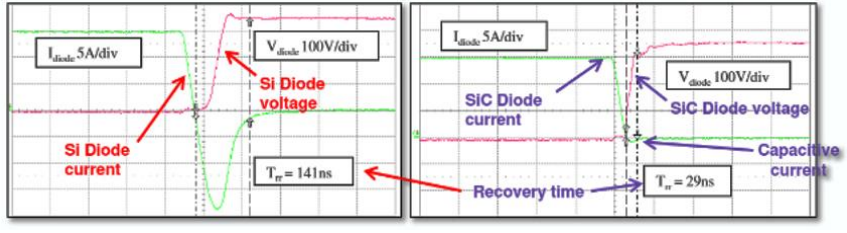
TO-247-4
Kelvin Pin
8mm Creepage
8nH Inductance

TO-263-7
Kelvin Pin
7mm Creepage
2nH Inductance

- Design for full load and high-power continuous power operation
- Select component that favors **lower conduction losses**



- Select lowest Qrr for faster recovery time and lower losses



22kW HIGH POWER DENSITY BI-DIRECTIONAL EV CHARGER – DC-DC [CRD-22DD12N]

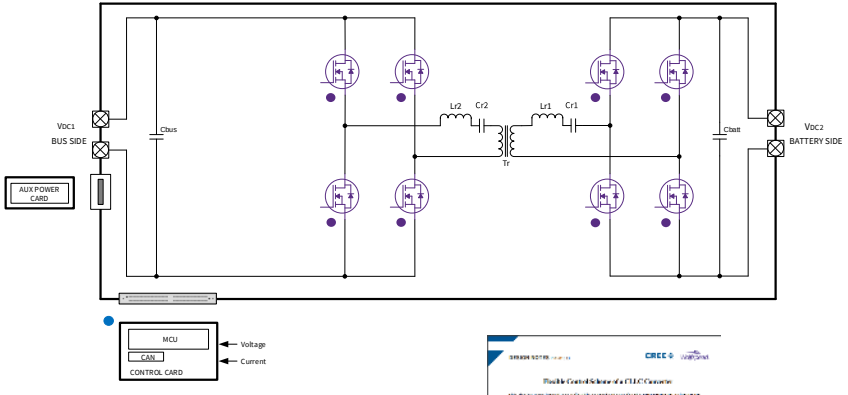
Design Specifications

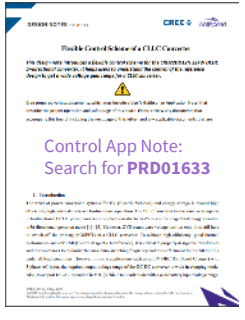
Topology	Resonant CLLC
Input Voltage	650V-900V |380V-900V| 360V-760V
Output	200V-800V
Power	22kW– 3Phase | 6.6kW – 1 phase
Direction	Bidirectional
Efficiency	>98.5%
Power Density	8kW/L
PWM Frequency	140kHz-250kHz
SIC MOSFET	8x C3M0032120K - Discrete
Control Scheme	Nom Output : PFM + Phase shift Low Voltage Output : Reconfigurable Adaptive SR control Low DC Link: Half Bridge High DC Link: Full Bridge
Magnetics	2x PQ Transformers Lm =12.8uH | 9.9uH

Key benefits
- Multiple operational modes supports
- DC Link from both 3-Phase AC and Single-Phase AC input
- 200VDC to 800V DC battery range

Tools & Resources

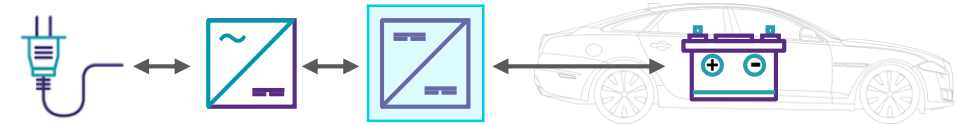
- Design Files: Schematics, BOM and BOM Analysis, Design Files
- Firmware on Request





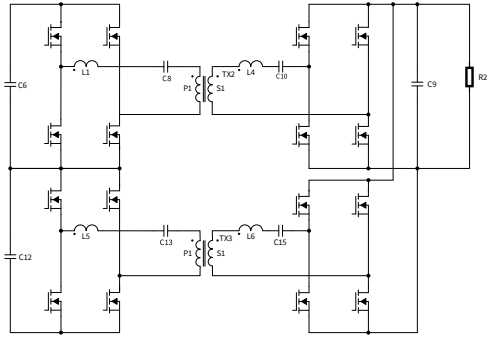
https://www.wolfspeed.com/crd-22dd12n

DC-DC SILICON VS. SILICON CARBIDE IN 22kW DC FAST CHARGERS

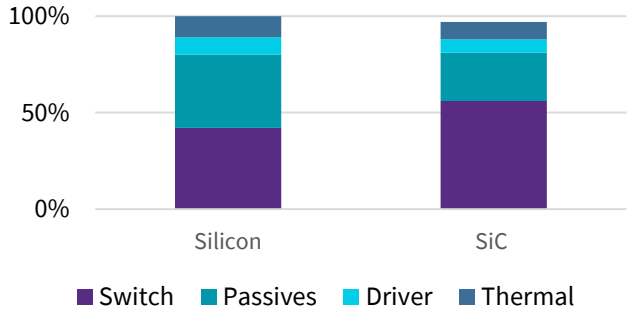


Silicon Design

- MOSFET 100kHz
- Power density 3.5kW/L
- Peak efficiency 97.5%

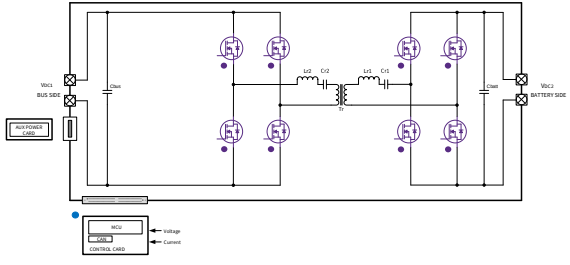


System Cost Comparison



Wolfspeed Full SiC Design

- 135-250kHz high operating frequency
- Peak efficiencies of 98.5%
- Power density of 8kW/L
- Flexible output voltage



Wolfspeed SiC enables 40% less losses with lower system cost

MOSFET SELECTION FOR LLC PRIMARY

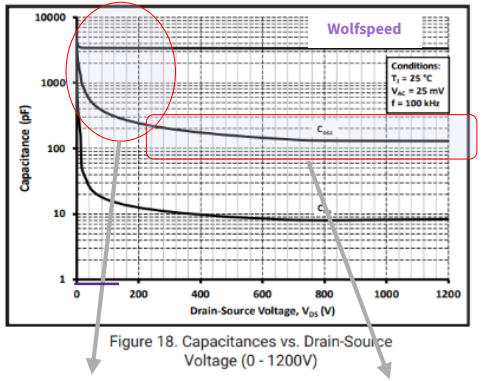
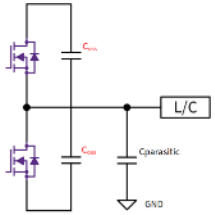
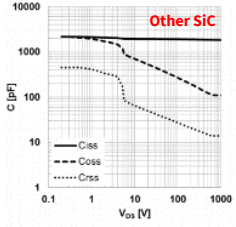


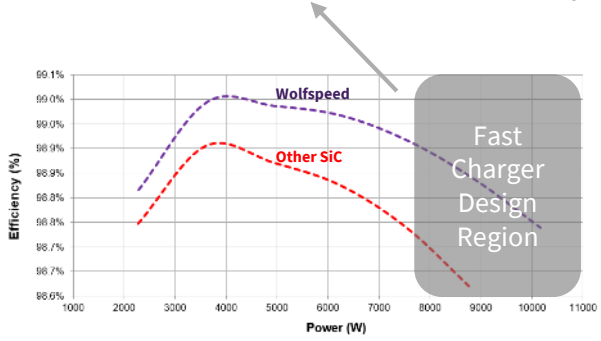
Figure 18. Capacitances vs. Drain-Source Voltage (0 - 1200V)



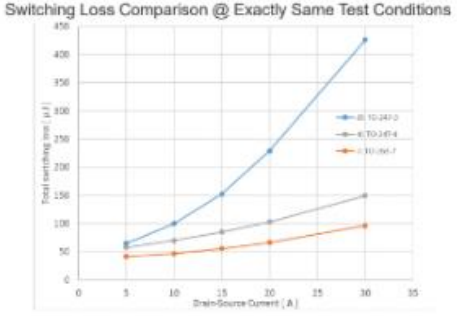


- Longest Coss discharge time in this region. Choose lowest and flattest Coss.

- $P(Loss)_{Switching}$ α Magnetizing current which is small for LLC
- Design and optimize at full load – conduction loss dominated region



- TO-247-4 and TO-263-7 are preferred due to lower oscillation

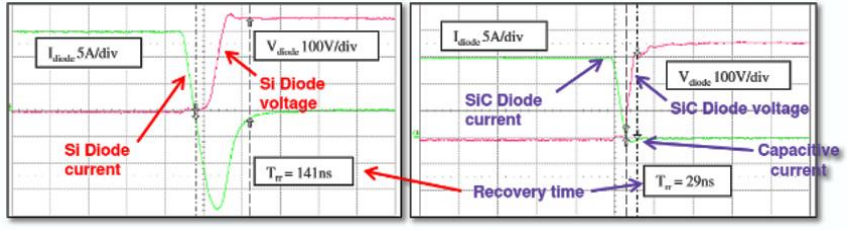


TO-247-3
NO-Kelvin Pin 2.6mm Creepage 8nH Inductance

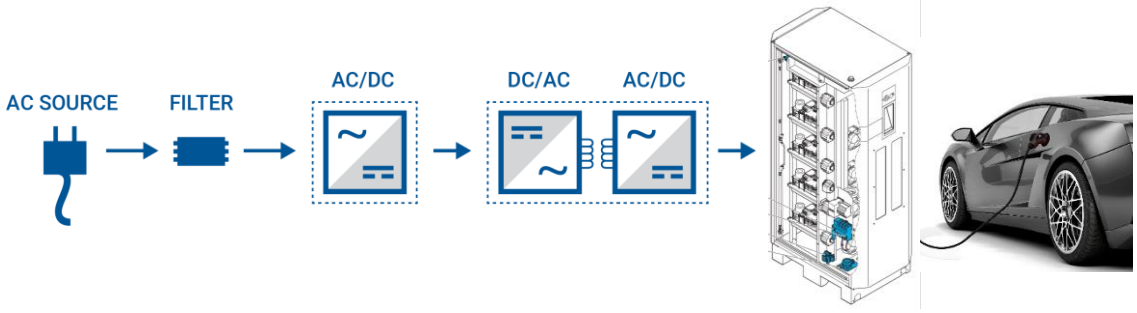
TO-247-4
Kelvin Pin
8mm Creepage
8nH Inductance

TO-263-7
Kelvin Pin
7mm Creepage
2nH Inductance

- Lowest Qrr for faster recovery time when operating out of ZVS
- Si MOSFET can be damaged due to poor body diode performance



POWER SYSTEM ARCHITECTURE AND ANALYSIS



SiC Advantage :

- 1-2% higher efficiency.
- 50% increase in power density,
- Lower system cost (smaller magnetics, less overall system cooling, smaller & cheaper mechanical housing).

15kW IGBT

20kW Wolfspeed SiC

Simplify & Save with SiC

E BOM Cost savings	**12-15% per 30kW**
Increase in power stage efficiency	**Up to 2%**
Power Density Improvements	**Up to 50%**
Charge pole cost	**$- Lower**
Charge pole size	**$- Smaller**

Wolfspeed Product Portfolio

WOLFSPEED 600V/650V SIC SCHOTTKY DIODE

Blocking Voltage (V)	Fwd. Current Rating (A)	TO-220-2	TO-220-F2 FullPAK	TO-220 Isolated	TO-247-3	TO-252-2	TO-263-2	QFN
								
650V/600V	2		C3D02060F			C3D02065E		
650V/600V	3		C3D03060F			C3D03065E		
650V/600V	4	C6D04065A	C3D04060F			C6D04065E		
650V/600V	6	C6D06065A	C3D06060F	C3D06065I		C6D06065E	C3D06060G C6D06065G	C6D06065Q
650V/600V	8	C6D08065A		C3D08065I		C6D08065E	C3D08060G C6D08065G E3D08065G	C6D08065Q
650V/600V	10	C6D10065A		C3D10065I		C6D10065E	C3D08060G C6D10065G	C6D10065Q
650V	12	C3D12065A						
650V	16	C3D16065A			C6D16065D			
650V	20	C6D20065A			C6D20065D E3D20065D		C6D20065G	
650V	30				C3D30065D E3D30065D			
650V	50				C6D50065D			

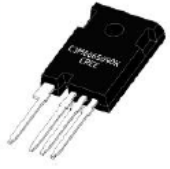
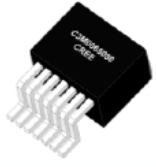
Industrial
Automotive
New Product

WOLFSPEED 1200V SIC SCHOTTKY DIODE

Fwd. Current Rating (A)	TO-220-2	TO-220-F2 FullPAK	TO-220 Isolated	TO-247-3	TO-252-2	TO-263-2	TO-247-2
							
2	C4D02120A				C4D02120E		
5	C4D05120A				C4D05120E		
8	C4D08120A				C4D08120E		
10	C4D10120A E4D10120A			C4D10120D	C4D10120E		C4D10120H
15	C4D15120A			C4D15120D			C4D15120H
20	C4D20120A E4D20120A			C4D20120D E4D20120D		E4D20120G	C4D20120H
30				C4D30120D			
40				C4D40120D			

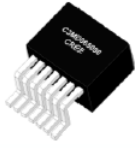
Industrial
Automotive
New Product

WOLFSPEED 650V SIC MOSFET

Rds(ON) 25°C (mΩ)	Forward Current Rating 100°C (A)	TO-247-3 'D'	TO-247-4 'K'	TO-263-7 'J'	TOLL 'L'
					
15	63	C3M0015065D	C3M0015065K		
25	70	C3M0025065D	C3M0025065K	C3M0025065J1	
45	35	C3M0045065D	C3M0045065K	C3M0045065J1	C3M0045065L
60	27	C3M0060065D	C3M0060065K	C3M0060065J	C3M0060065L
120	16	C3M0120065D	C3M0120065K	C3M0120065J	C3M0120065L

Industrial
Automotive
New Product

WOLFSPEED 1200V SIC MOSFET

Rds(ON) 25°C (mΩ)	Forward Current Rating 100°C (A)	TO-247-3 'D'	TO-247-4 'K'	TO-263-7 'J'
				
16	85	C3M0016120D	C3M0016120K	
21	74	C3M0021120D	C3M0021120K	
32	48	C3M0032120D	C3M0032120K	C3M0032120J1
40	48	C3M0040120D	C3M0040120K	
75	12.7	C3M0075120D E3M0075120D	C3M0075120K E3M0075120K	C3M0075120J
160	17	C3M0160120D		C3M0160120J
350	5	C3M0350120D		C3M0350120J

Industrial
Automotive
New Product

WOLFSPEED 1700V SIC MOSFET

Rds(ON) 25°C (mΩ)	Forward Current Rating 25°C (A)	TO-247-3 'D'	TO-247-4 Plus 'P'	TO-263-7 'J'
				
45	72	C2M0045170D	C2M0045170P	
80	40		C2M0080170P	
1000	5	C2M1000170D		C2M1000170J

Industrial
Automotive
New Product

Reference Design Overview

Full Bi-directional OBC system

- 6.6kW bi-directional OBC

- Using C3M 650V SiC MOSFET
- Highest power density (3.3kW/L)
- Peak efficiency = 97%
- Full paper design and limited number of HW units

- 22kW bi-directional OBC

22kW Bi-Directional DCDC Converter

- Using C3M 1200V SiC MOSFET
- Highest power density (8kW/L)
- Peak efficiency = 98.6%
- Full paper design and limited number of HW units

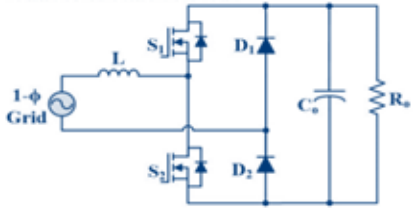
22kW Bi-Directional ACDC Converter

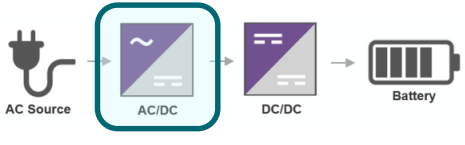
- Using C3M 1200V SiC MOSFET
- Highest power density (4.6kW/L)
- Peak efficiency = 98.6%
- AVAILABLE SOON

Uni-directional AC/DC block

- 2.2kW bridgeless totem-pole PFC

- 2 x C3M0060065D + 2 x Si PN diode
- Peak efficiency = 98.5%

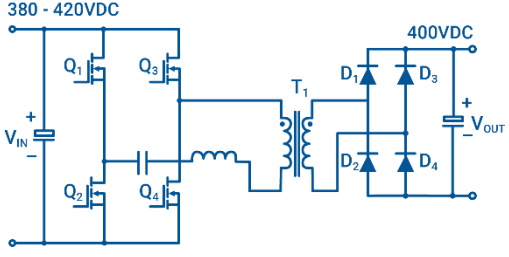


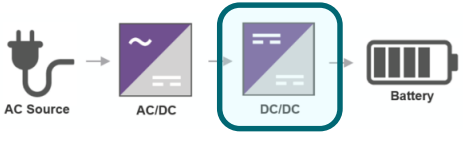


Uni-directional DC/DC block

- 6.6kW LLC DC/DC Converter

- 4 x C3M0060065D + 4 x C6D10065A
- Peak efficiency > 98%
- ZVS enables >500kHz switching frequency





REFERENCE DESIGN AND SUPPORTING TOOL

Electrical simulation

https://www.wolfspeed.com/speedfit

https://go.wolfspeed.com/all-models

Reference designs

https://www.wolfspeed.com/power/products/reference-designs

Application	Reference design name	Topology
Automotive	6.6 kW Bi-Directional EV On-Board Charger	AC to DC, DC to AC
Automotive	22kW Bi-directional High Efficiency DC/DC Converter	Bi-Directional DC to DC
Automotive & Renewable Energy	22kW Bi-directional High Efficiency Active Front End (AFE) Converter	Bi-Directional AC to DC
Renewable Energy	60 kW Interleaved Boost Converter	DC to DC
Server Power supply	2.2 kW High Efficiency (80+ Titanium) Bridgeless Totem-Pole PFC with SiC MOSFET	AC to DC
Server Power supply	6.6 kW High Frequency DC-DC Converter	DC to DC

THANK YOU