Wolfspeed SiC를 이용한 미래형 EV, 그린에너지, 전력시스템 설계 및 구현

Wolfspeed | 이태훈 부장 FSE
함정호 부장 FAE
| JAN18 2022

AGENDA

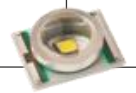
1. Introduction of SiC and Wolfspeed
2. Advantages of Silicon Carbide (SiC)
3. Wolfspeed SiC Application Design
4. Tips of Gate Driving with SiC MOSFETs

INTRODUCTION OF SIC AND WOLFSPEED

BRIEF HISTORY OF SIC AND WOLFSPEED

https://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_a/advanced/ta_1_3.html

- In contrast to diamonds, **SiC** is never found on this world (and thus never became a valued gemstone in the past). Only in fragments of other worlds (i.e. **meteorites**), on occasion contain **SiC** as has been found by **Moissan** in **1905**. Mineralogists thus call "natural" **SiC** " **Moissanite**".
- In **1955**, **Lely** made the next big step in inventing the "**Lely growth method**" to grow **SiC** crystal
- **1987 Cree** Research Inc., the first commercial supplier of **SiC** substrates, was founded



1987 Founded out of North Carolina State University

1989 Commercialized the World's **first silicon carbide Blue LED**

1991 Released world's **first commercial silicon carbide wafers**

1993 Listed on Nasdaq

1998 Created industry's first GaN HEMT on SiC

2000 Demonstrated first-ever GaN MMIC with record power density

2002 Released **first 600V commercial silicon carbide JBS Schottky diode**

2006 Started the LED Revolution with the first lighting class LED

2006 Released industry's **first 1200V silicon carbide Schottky diode**

2011 Released industry's **first silicon carbide MOSFET**

2013 Brought the LED bulb mainstream – forced the industry to respond

2014 Became Department of Defense Trusted GaN Foundry

2015 Exceeded 2 trillion field hours with Power products

2016 Shipped GaN RF devices surpassing 1.3 Gigawatts output power

2016 Leading 150mm silicon carbide wafer market; **introduced 200mm**

2017 Gregg Lowe named new CEO

2018 Acquired Infineon RF Power Business

2019 Selected as silicon carbide partner for the Volkswagen Group FAST Program

2022 New York Mohawk Valley Fab up and **running with 200mm wafer**

…AND OPENING THE WORLD'S LARGEST SILICON CARBIDE FAB

The Mohawk Valley Fab in NY will open in 2022

484,000

SQ FT STATE-OF-THE-ART FABRICATION FACILITY

>30x

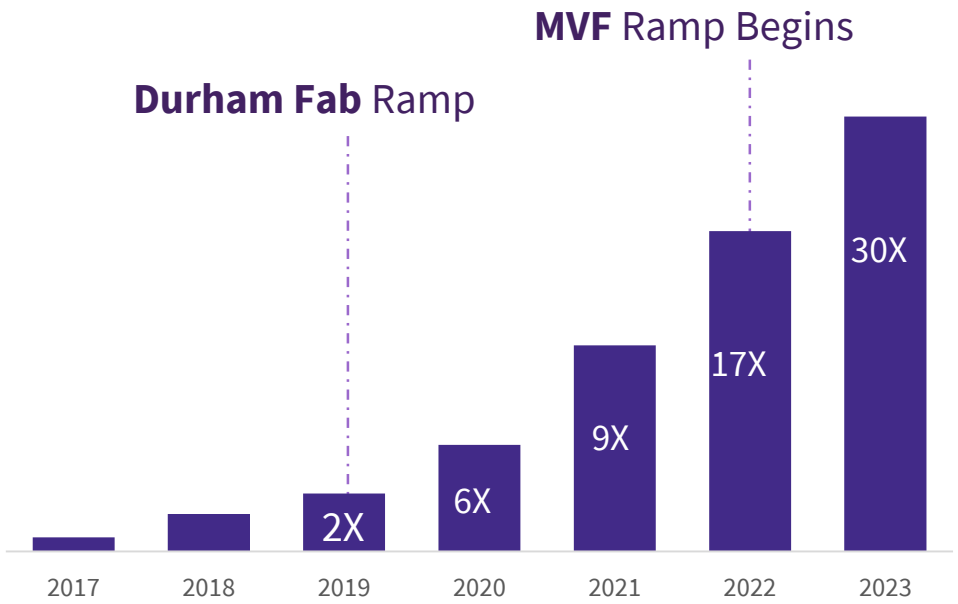
INCREASE IN SILICON CARBIDE WAFER FABRICATION PRODUCTION

200mm

AUTOMOTIVE-QUALIFIED PRODUCTION FACILITY

BUILDING A POWERHOUSE SEMICONDUCTOR COMPANY

- Accelerating Capital **Investment** Plan
- Ramping Mohawk Valley at **200mm**
- Renaming the Company **Wolfspeed**



Capacity expansion

Strengthen supply chain

Reduce the cost

Provide state of art technology

Accelerate time to market

NEW NAME, NEW TICKER—SAME DEDICATED PARTNER

WHAT'S CHANGED

- On October 4, 2021, we officially began operating as Wolfspeed, Inc. and trading under the ticker symbol "WOLF" on the NYSE.
- This marks the culmination of our transformational journey as we now lead the industry transition from silicon to Silicon Carbide as a pure-play, global semiconductor powerhouse.

WHAT IT MEANS

- This is a natural progression that builds on our unsurpassed reputation of developing silicon carbide solutions and capitalizes on the competitive positioning the Wolfspeed brand has in the market.
- By sharpening our focus on our portfolio of silicon carbide products, we're now in the best position to lead a once-in-a-generation technology shift and create the products and materials that our customers use to power a cleaner, better future.

WOLFSPEED AT A GLANCE

Headquarters: Durham, North Carolina

Founded: 1987

Global Footprint: 17 Countries

Website: www.wolfspeed.com

Stock Symbol: WOLF

Stock Exchange: NYSE

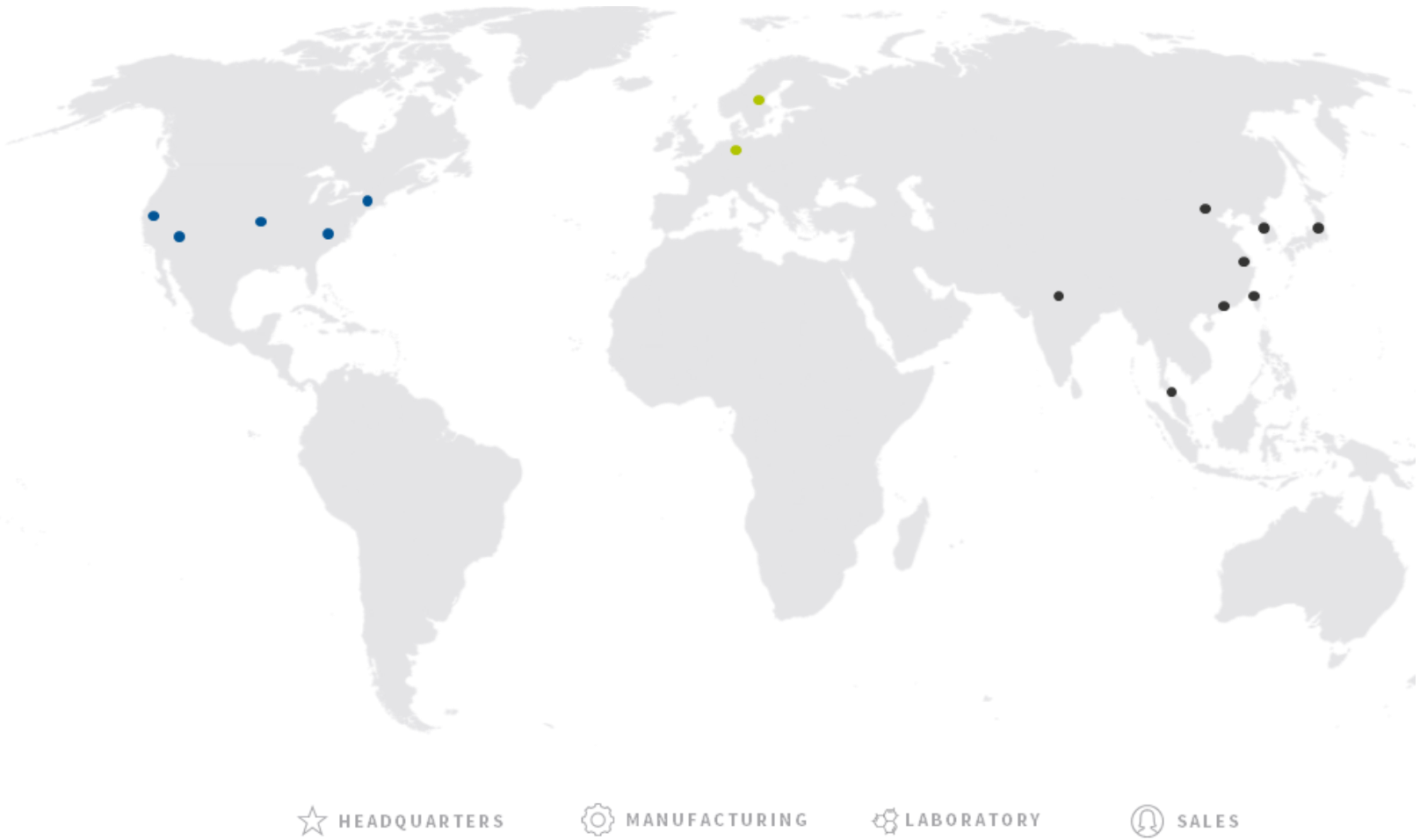
People: ~3,500 Employees

History: 30+ years of technology leadership

Revenue: $525.6M in FY2021

Innovation: ~2,140 Issued Patents

REGIONAL OFFICES



NORTH AMERICA

RTP / Durham, NC	☆ ⚙ ⚗ 🔔
Fayetteville, AR	⚙ ⚗
Mesa, AZ	⚗
Morgan Hill, CA	⚙ ⚗ 🔔
Marcy, NY	⚙ ⚗

EUROPE

Munich, Germany	🔔 ⚗
Kista, Sweden	🔔 ⚗

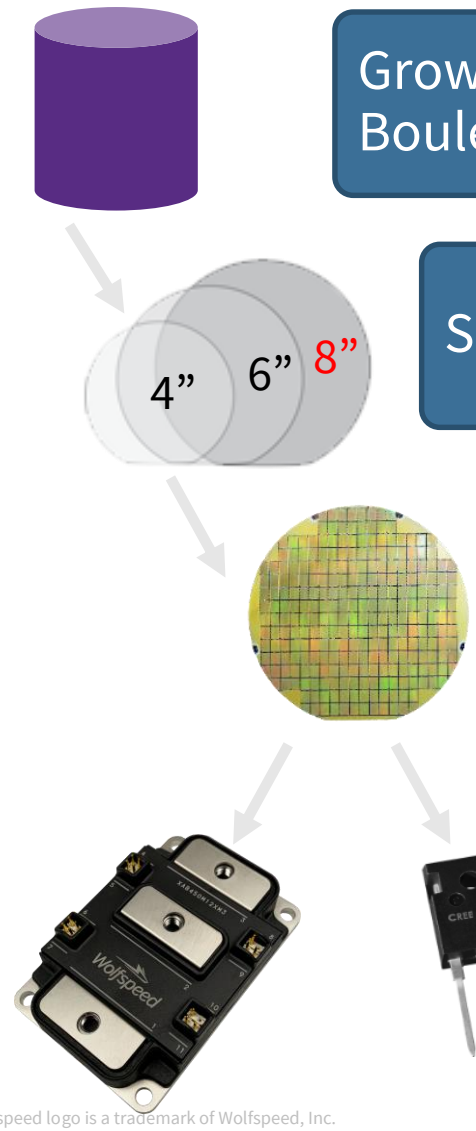
ASIA

Hong Kong	🔔
India	🔔
Japan	🔔 ⚗
Korea	🔔 ⚗
Malaysia	🔔
Shanghai	🔔 ⚗
Shenzhen	🔔 ⚗
Taiwan	🔔 ⚗

A GLOBAL, PURE-PLAY SEMICONDUCTOR POWERHOUSE

Wolfspeed®

Products	Applications
Materials	EVs
Schottky Diodes	EV Charging Infrastructure
MOSFETs	Renewables
Power Modules	Energy Storage
RF Gan on SiC	Data Centers
MMICs/ HEMTs	Communications Infrastructure
Bare Die	Radar
	Aerospace and Defense



Grow Silicon Carbide Boules

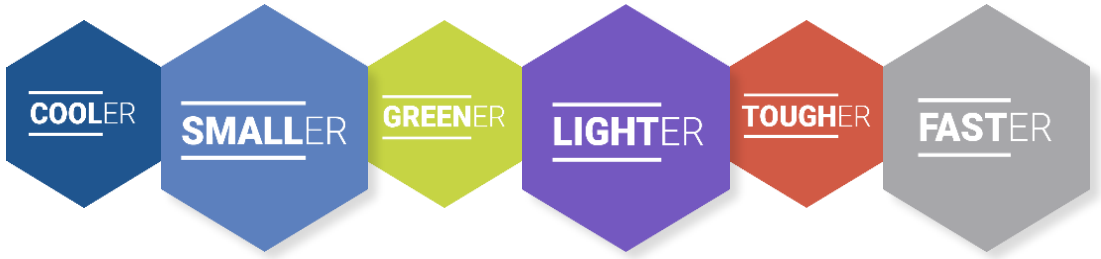
Slice & Polish Wafers

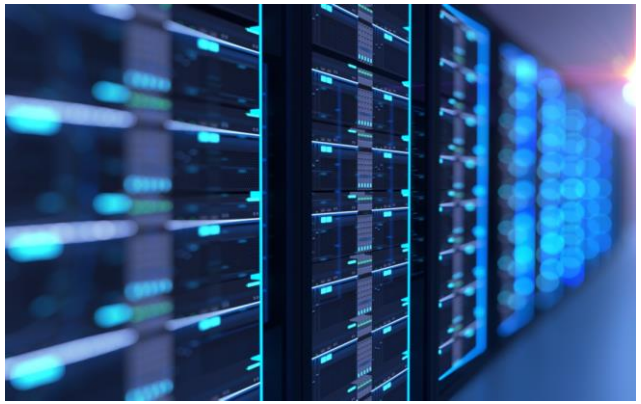
Grow Epi & Fabricate Devices

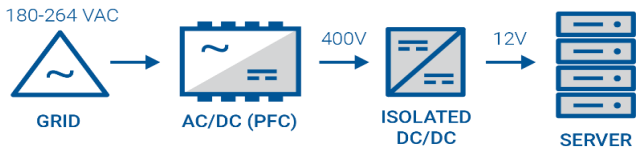
Package Die

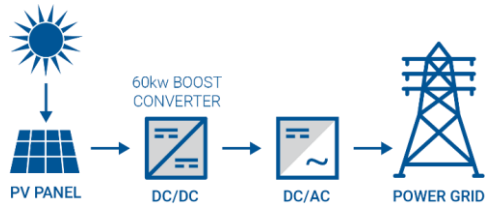
INDUSTRIAL APPLICATION

- ✓ **Fast Charger for Electric Vehicles**
- ✓ **High Efficiency Power for Data Centers**
- ✓ **Inverters for Solar Power and Energy Storage**
- ✓ **Low Power Auxiliary SMPS**









POWERING THE FUTURE

www.wolfspeed.com

Power Product Portfolio at a Glance

SiC Schottky Diodes and MOSFETS

- Up to 1700V rating
  - Diodes: 600V to 1700V
  - MOSFETs: 900V to 1700V (650V coming Q4 19)
- Up to 100A current rating (package limited)

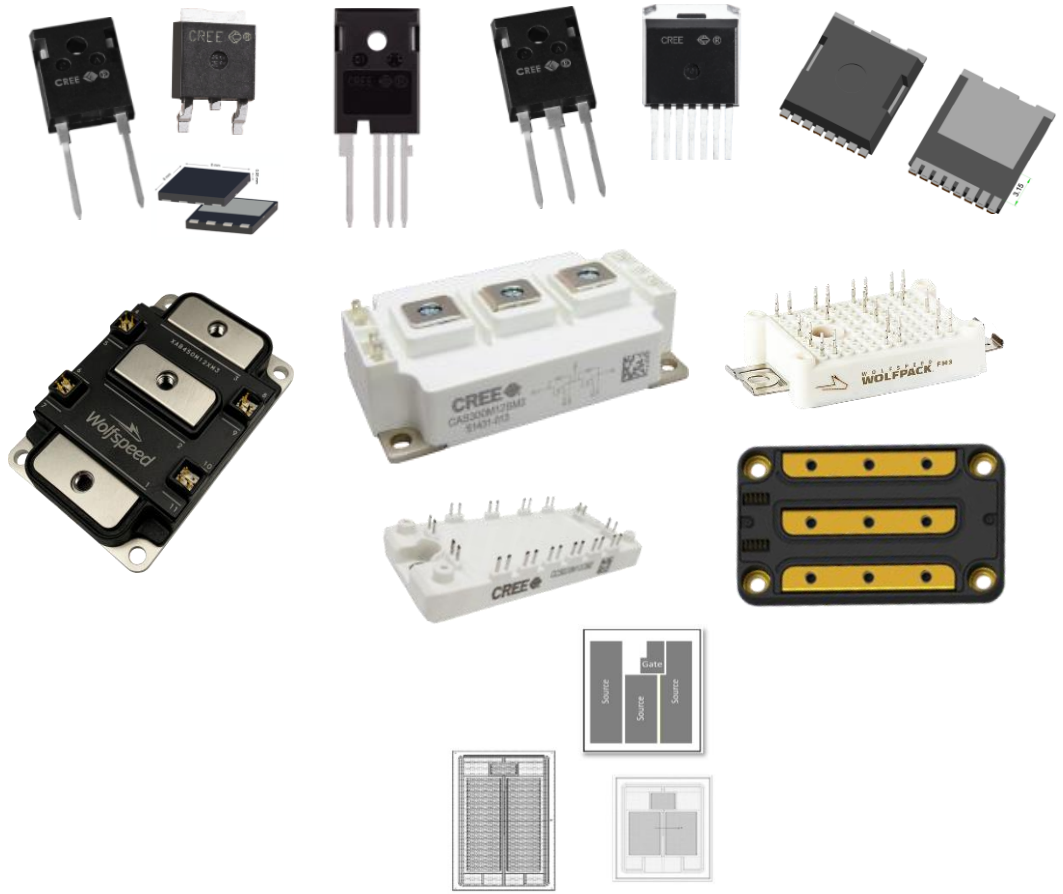
SiC Power Modules

- Up to 1700V rating
- Up to 450A current rating
- Half-bridge and three-phase configurations

SiC Bare Die Schottky Diodes and MOSFETs

- Up to 1700V rating
- Up to 196A current rating

Example Package Options



THE WOLFSPEED ADVANTAGE

Design Support Tools

Evaluation kits for all discrete packages

>16 reference design and demo boards for different applications

Enabling faster and easier design with Wolfspeed SiC

Gate driver reference designs

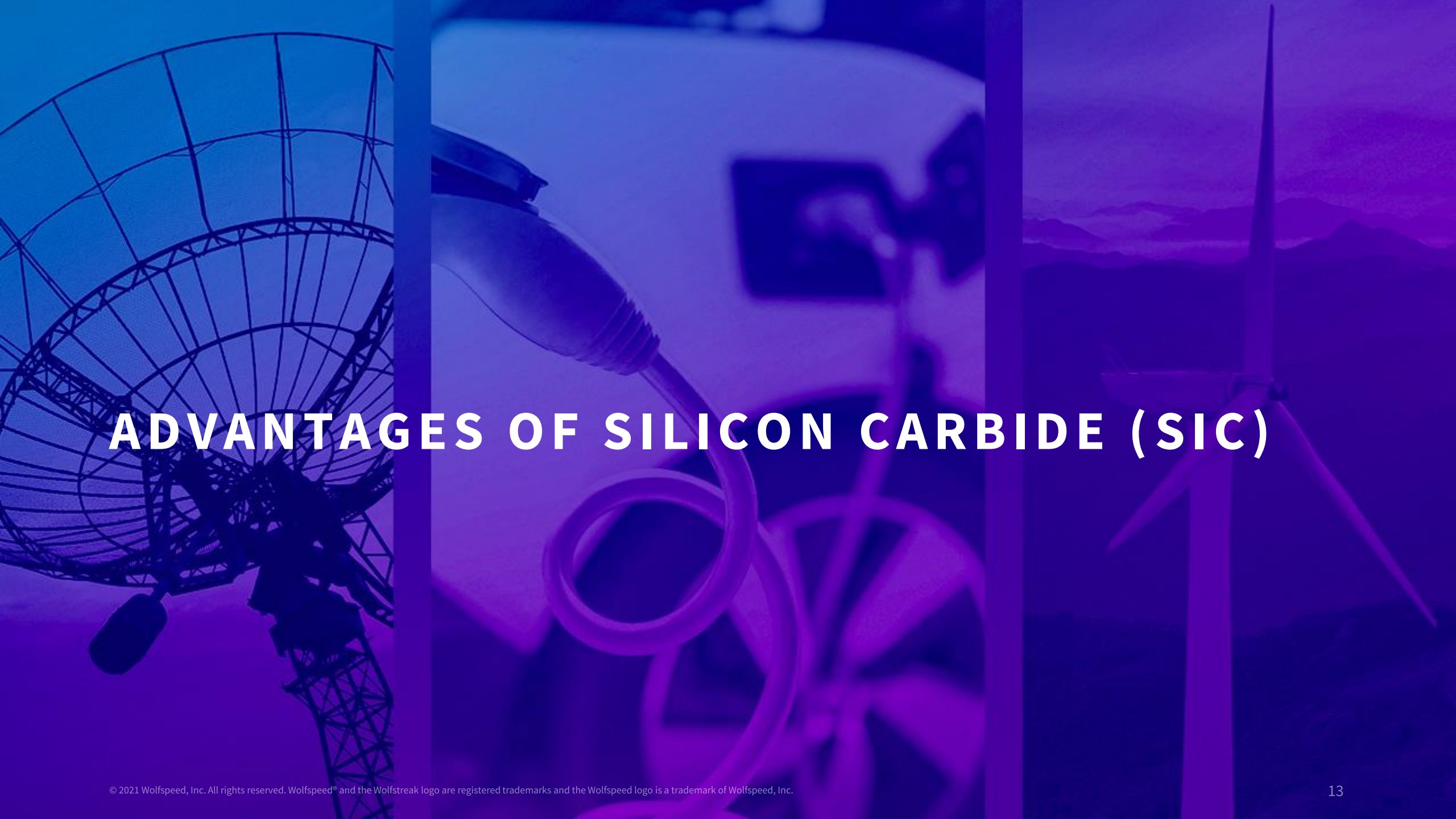
Online and offline simulation tools and models

SpeedFit™

LINEAR TECHNOLOGY

OrCAD CADENCE PCB SOLUTIONS

plecs Simulation Software for Power Electronics



ADVANTAGES OF SILICON CARBIDE (SIC)

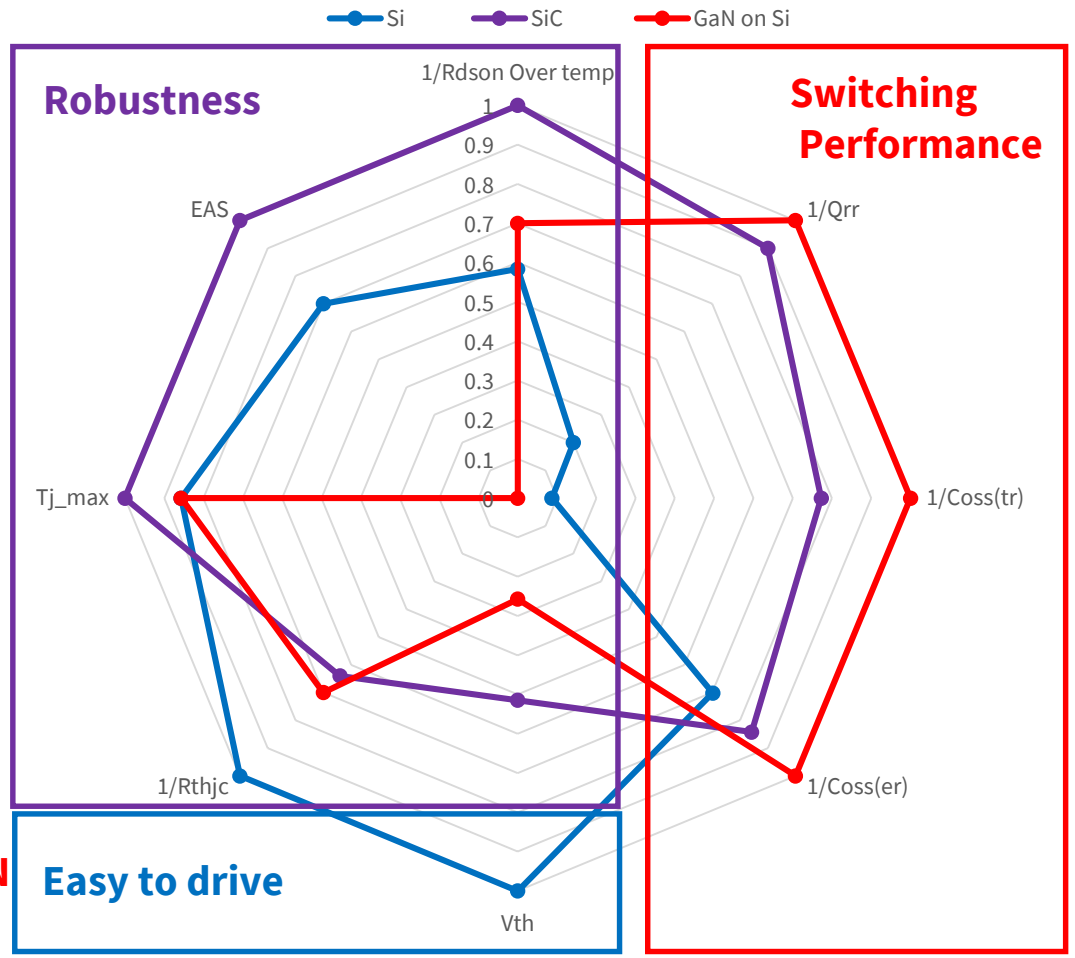
ADVANTAGES OF SILICON CARBIDE (SIC)
KEY PARAMETERS COMPARISON SI VS. SIC VS. GAN

Tj_max → Higher is better.
Robustness
Winner: **SiC**

EAS → Higher is better.
Robustness
Winner: **SiC. No EAS capability for GaN**

Rthjc → Lower is better.
Thermal performance
Winner: **Si**

Vth → Higher is better.
Immunity to noise. Easy to drive
Winner: **Si. Very low Vth for GaN**



Rdson over temp → Lower is better.
Lower loss @high T→ High efficiency, deliver higher power,
Winner: **SiC**

Qrr → Lower is better.
Switching loss for CCM sync rectifier
Winner: **GaN, SiC is close to GaN**

Coss(tr) → Lower is better.
dead time / Lm design → high frequency and efficiency
Winner: **GaN, SiC is close to GaN**

Coss(er) → Lower is better.
Minimum switching losses in hard-switching topologies
Winner: **GaN, SiC , Si is not too bad**

WOLFSPEED SIC APPLICATION DESIGN

APPLICATION:

EV Fast Charging

WHAT: Fast charging DC stations: 30 min charge duration. Bypasses OBC for rapid direct battery charging.

WHERE: PHEV, BEV battery charging 90kW – 350kW (average 160kW).

- DC charge from station to car.
- Typically today constructed from multiple 20-30kW blocks.

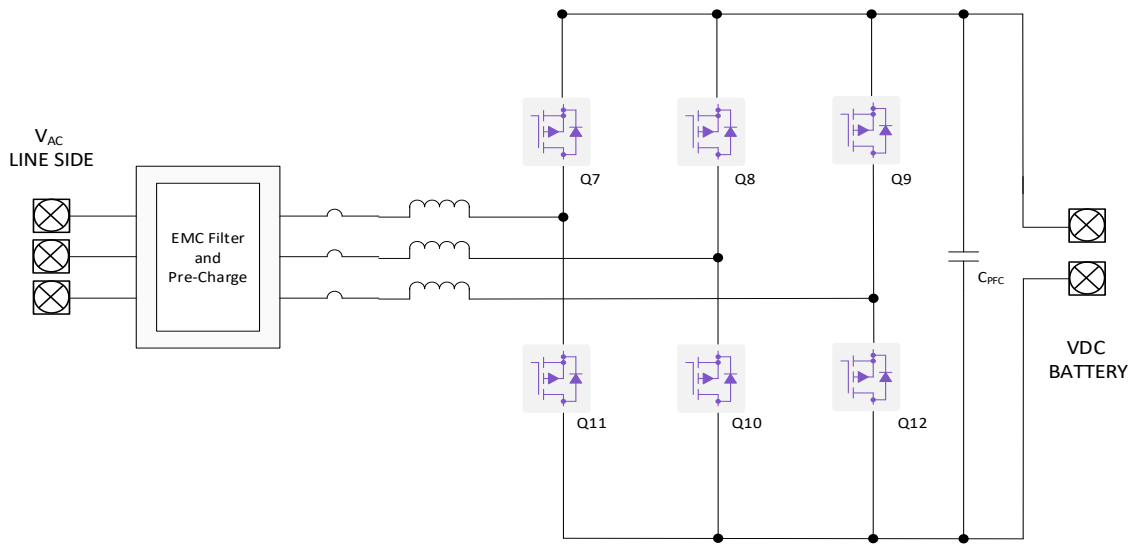
WHY: System cost, System efficiency, Power density (smaller stations), charger maintenance/up time. Future trends bidirectional energy flow

SIC ADVANTAGE:

- ~1-2% higher efficiency, 35-50% increase in power density at comparable system costs
- Less overall system cooling, smaller and cheaper mechanical housing
- Enables better Bidirectional charging for V2G / V2H

3-PHEASE 2-LEVEL ACTIVE FRONT END (AFE) | BI-DIRECTIONAL

AFE at 45KHz, 800V DC Link



BENEFITS

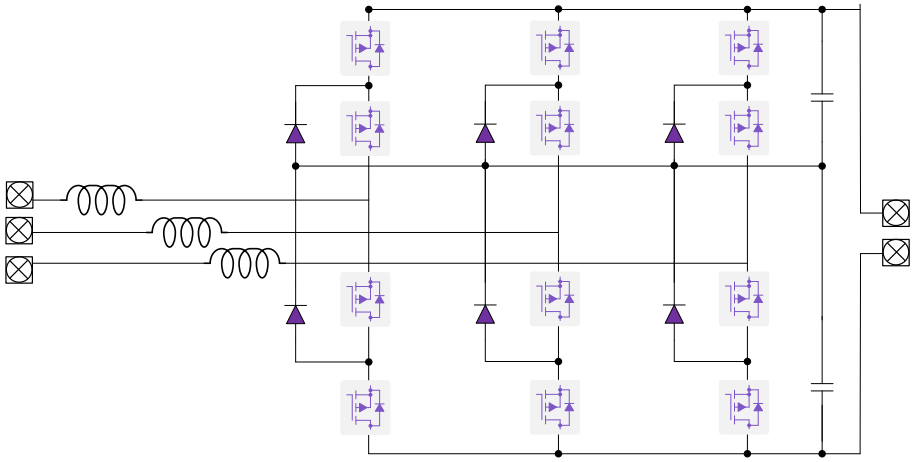
- 1200V SiC enables **Simple** 2-Level bidirectional AFE
- SiC enables **Smaller choke** with 2.5x Fsw
- Low component count and **Low Cost**
- **Mature** Control Scheme

6 x 1200V 32mOhm Discrete SiC MOSFET (22kW) or
1 x CCB021M12FM3 Wolfspeed WolfPACK(25kW) or
2 x CCB021M12FM3 Wolfspeed WolfPACK(50kW)

Cost	IGBT	SiC
Switch	32%	62%
Choke	40%	19%
Driver	9%	9%
Thermal	19%	10%

METRIC	IGBT	SiC
Fsw	20kHz	45kHz
Power Density	3.5kW/L	4.5kW/L
Efficiency	97.2%	98.2%

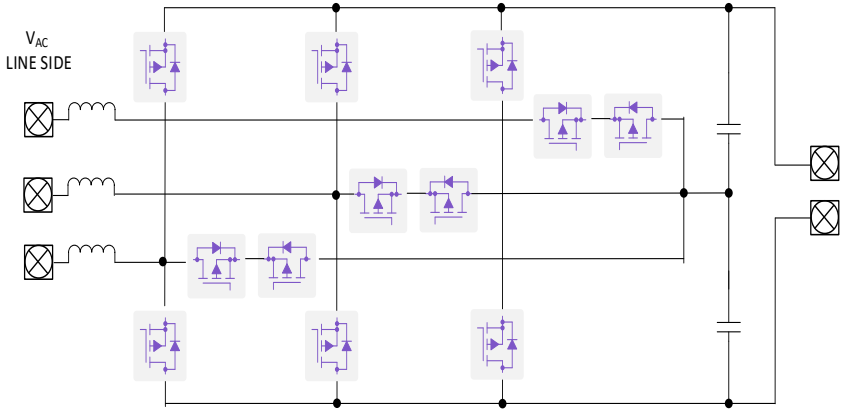
20-30KW NPC, TNPC AC-DC CONVERTER | BI-DIRECTIONAL



12x 650V SiC 25mOhm MOSFET +
6x 650V 16A SiC Schottky Diode

SiC BENEFITS vs Si

- Simple Si to SiC transition
- SiC Diode eliminates reverse recovery current for higher efficiency
- Lower power loss

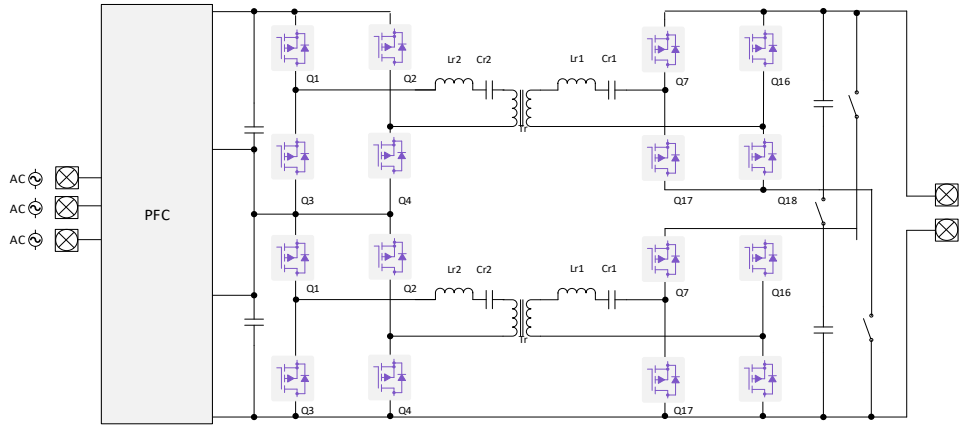


6x 1200V 32mOhm SiC (Outer) +
6x 650V SiC 45mOhm MOSFET (Mid)

SiC BENEFITS vs Si

- 1200V SiC enables high frequency operation (>45kHz)
- Reduce magnetics size
- Lower power loss

20-30KW CASCADE LLC/ 2LEVEL LLC DC-DC CONVERTER | BI-DIRECTIONAL

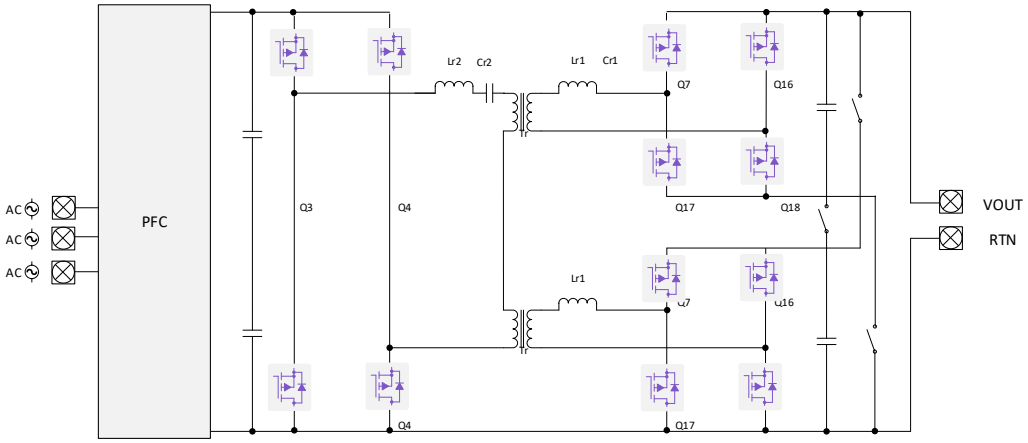


8x 650V 45mOhm SiC MOSFET's

8x 650V 45mOhm SiC MOSFET's

SiC BENEFITS vs Si

- Simple Si to SiC transition
- SiC enables high frequency operation (up to 200kHz)
- Lower power Loss



4x 1200V 32mOhm SiC MOSFET or
2x CAB016M12FM3 Power Module

8x 650V 25mOhm SiC MOSFETs

SiC BENEFITS vs Si

- 1200V SiC enables 2 Level design
- Series LLC Transformer
- SiC enables high frequency operation (up to 200kHz)
- Lower power Loss

WOLFSPEED SIC IN DC FAST CHARGER APPLICATIONS

STACKABLE POWER BLOCKS - BIDIRECTIONAL

STACKABLE POWER BLOCKS – UNIDIRECTIONAL

SUPER STATION - UNIDIRECTIONAL

20kW **30kW** **50kW** **100kW** **300kW** **600kW**

Discrete Blocks (20kW) **x 1**

Discrete Blocks (20kW) **x 3**

Discrete Blocks (30kW) **x 6**

Discrete Blocks (60kW) **x 6**

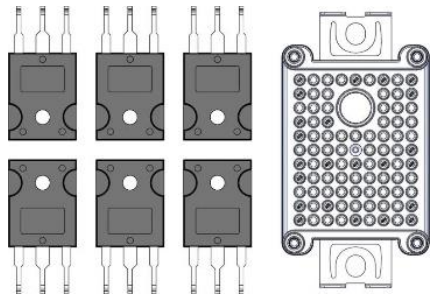
Discrete Blocks (60kW) **x 10**

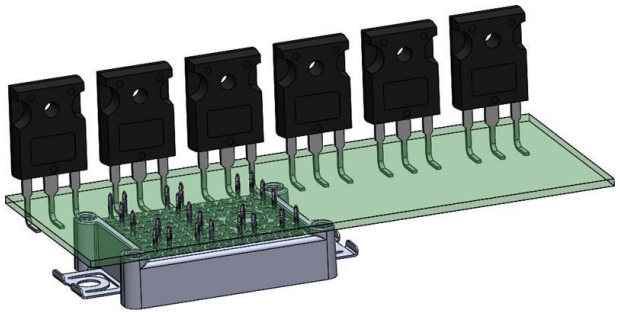
Module Block (25kW) **x 2**

Module Block (50kW) **x 4**

Module Block (50kW) **x 8**

High Power Integrated Design





APPLICATION:
Solar Power

IGBT based 10kW Solar Inverter
Forced air cooling, must be de-rated over 45C ambient

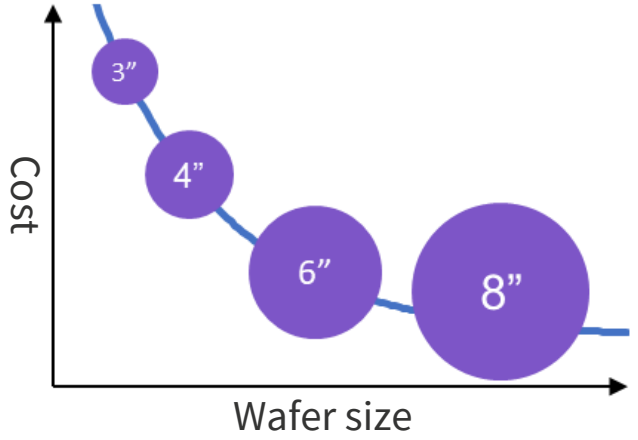
Wolfspeed SiC MOSFET based 10kW Solar Inverter
Passive cooling, no de-rating up to 55C ambient

WHAT: SiC MOSFETs and Diodes in PV DC/DC and DC/AC, DC/DC for ESS(optional)

WHERE: Panel array boost converter to provide input voltage for ESS and/or power grid inverter

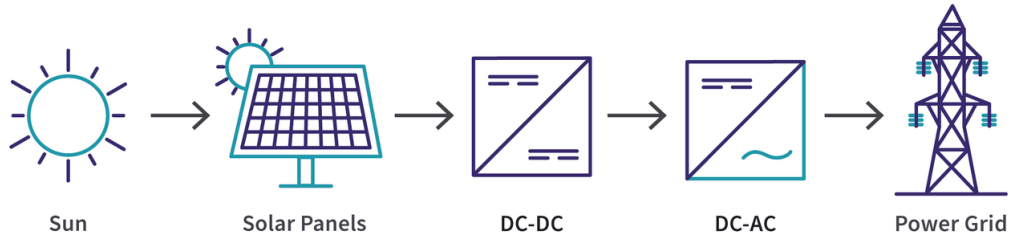
WHY: Minimize size and weight while increasing ruggedness for lower installation and maintenance costs

Aluminum Price from 2016-2021

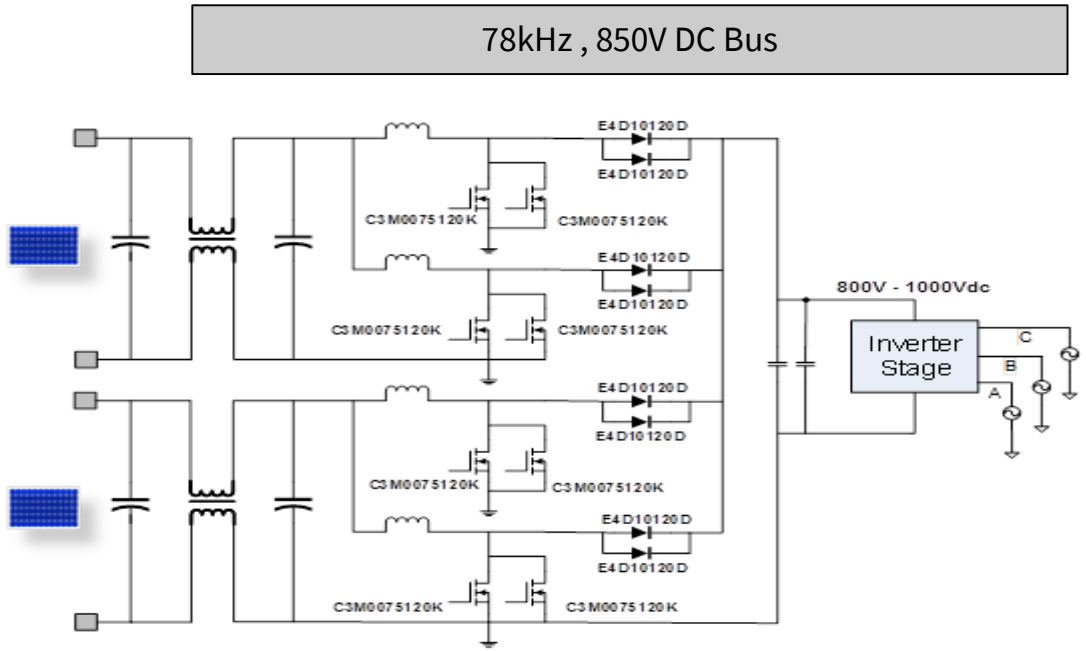


SIC ADVANTAGE :

- Up to 3X smaller size
- 10X lighter weight



60KW SIC BASED INTERLEAVED BOOST CONVERTER REFERENCE DESIGN



- 2X C3M0075120K MOSFETs in parallel per channel
- 2X C4D10120D boost diodes

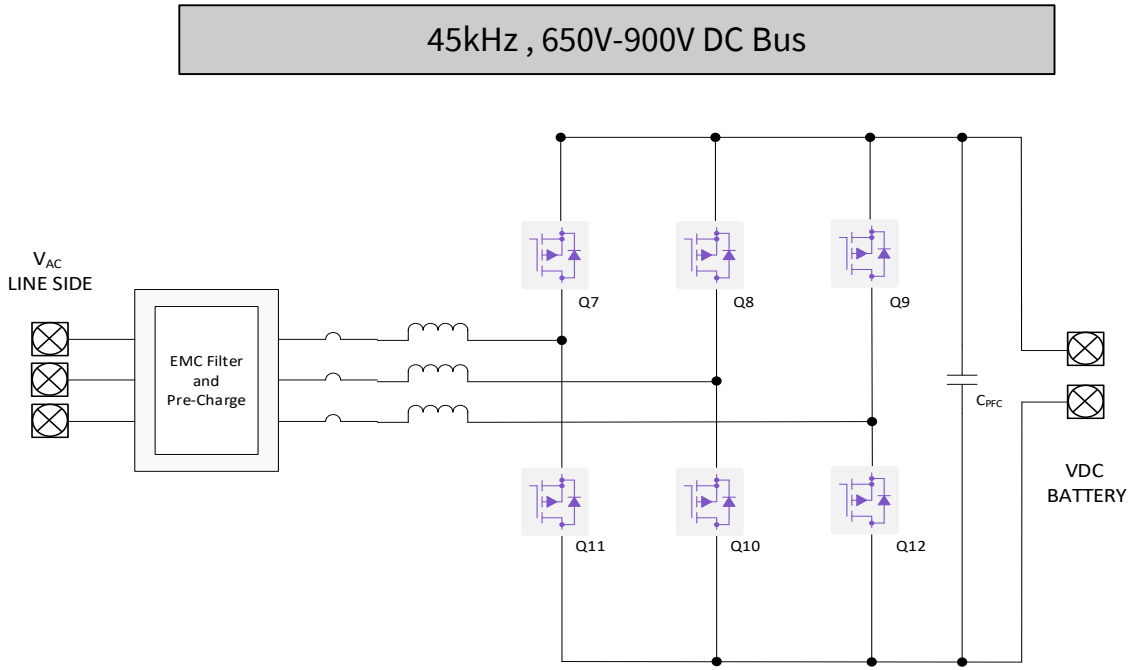
Reference design link:
https://www.wolfspeed.com/products/power/reference-designs/crd-60dd12n

Parameters	Value
Input voltage range	470VDC-800VDC
Output Voltage	850VDC
Output Power	60kW (Vin ≥ 600V) 50kW (Vin < 660v)
Switching Frequency	78kHz
Efficiency	99.5%
Power Density	127W/in^3
Topology	Interleaved Boost
Power Device Package	TO-247-4

C3M0075120K

C4D10120D

BI-DIRECTIONAL ACTIVE FRONT END (AFE) REFERENCE DESIGN



Parameters	Value
AC Input Voltage	304Vac – 460 Vac(3phase); 90Vac – 265Vac(single phase)
Power @3phase	22kW Max, power derating <380Vac
Power @1phase	6.6kW Max; power derating <215Vac
DC output voltage	650V-900V
PCBA Dimensions	366mmx186mmx70mm (4.5kW/L)
Peak Efficiency	>98%
Switching Frequency	45kHz

- C3M0032120K MOSFETs per arm

Reference design link:
https://www.wolfspeed.com/products/power/reference-designs/crd-22ad12n

C3M0032120K

APPLICATION:

Data Center(Server) Switch Mode Power Supply

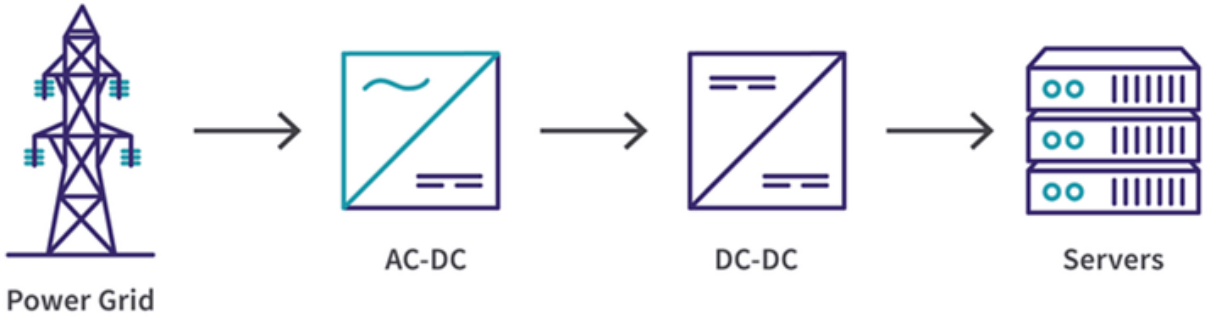
WHAT: Silicon Carbide MOSFETs and Diodes

WHERE: Data center switch mode power supplies

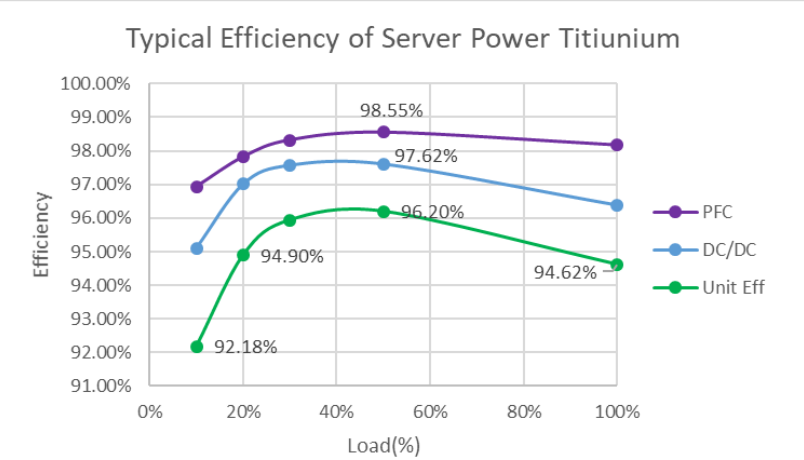
WHY: Maximize output while minimizing energy consumption

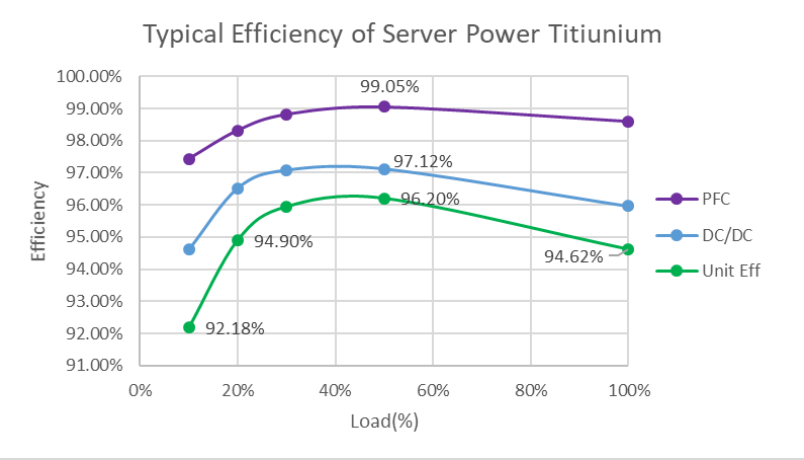
SIC ADVANTAGE:

- Increases efficiency
- Reduces size
- Superior thermals



EFFICIENCY STANDARD OF SMPS FOR DATA CENTER





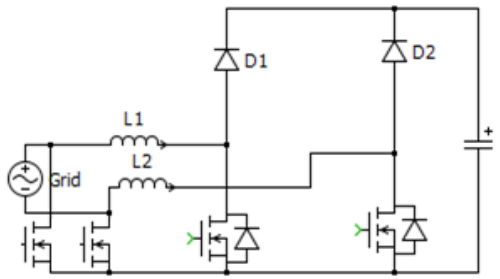
Requirement	Output/Load	Efficiency 10%	Efficiency 20%	Efficiency 50%	Efficiency 100%	Power Factor[1] 10%	Power Factor[1] 20%	Power Factor[1] 50%	Power Factor[1] 100%	80PLUS 115V non-redundant	80PLUS 115V Industrial
Energy Star 3.0	multi	---	90%	92%	89%	---	0.80	0.90	0.95	Platinum	Platinum
	single ≤ 500W	83%	90%	94%	91%	---	0.80	0.95	0.95	Titanium[2]	---
	500W < single ≤ 1000W					0.65	0.80	0.95	0.95	Titanium[2]	---
	single > 1000W					0.80	0.90	0.95	0.95	Titanium[2]	---
Requirement	**Output/Load**	**10%**	**20%**	**50%**	**100%**	**10%**	**20%**	**50%**	**100%**	**230V non-redundant**	**230V redundant**
Lot 9 (1-Mar-2020)	multi	---	88%	92%	88%	---	---	0.90	---	Gold	Gold
	single	---	90%	94%	91%	---	---	0.95	---	Platinum[2]	Platinum
Lot 9 (1-Jan-2023)	multi	---	90%	94%	91%	---	---	0.95	---	Platinum[2]	Platinum
	single	90%	94%	96%	91%	---	---	0.95	---	Titanium	Titanium

80 Plus test type / Percentage of rated load	Icon	115 V internal non-redundant 10%	20%	50%	100%	230 V internal redundant 10%	20%	50%	100%	230 V EU internal non-redundant 10%	20%	50%	100%
80 Plus	80 PLUS		80%	80%	80%						82%	85%	82%
80 Plus Bronze	80 PLUS BRONZE		82%	85%	82%		81%	85%	81%		85%	88%	85%
80 Plus Silver	80 PLUS SILVER		85%	88%	85%		85%	89%	85%		87%	90%	87%
80 Plus Gold	80 PLUS GOLD		87%	90%	87%		88%	92%	88%		90%	92%	89%
80 Plus Platinum	80 PLUS PLATINUM		90%	92%	89%		90%	94%	91%		92%	94%	90%
80 Plus Titanium	80 PLUS TITANIUM	90%	92%	94%	90%	90%	94%	96%	91%	90%	94%	96%	94%

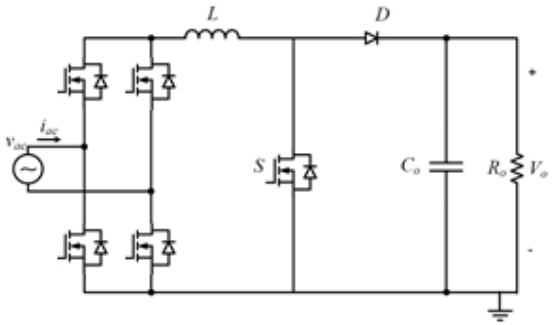
- >98.5% PFC peak efficiency is required for 80plus Titanium applications.
- Two approaches are available. (1) DC/DC 97.62% (2) PFC 99.05%

TOPOLOGIES OF PFC

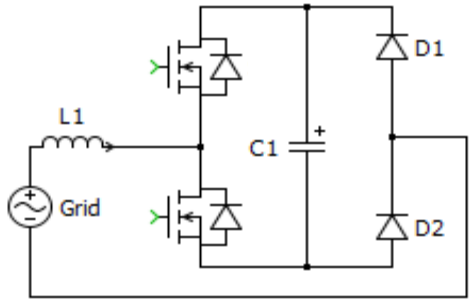
Dual Boost Bridgeless PFC



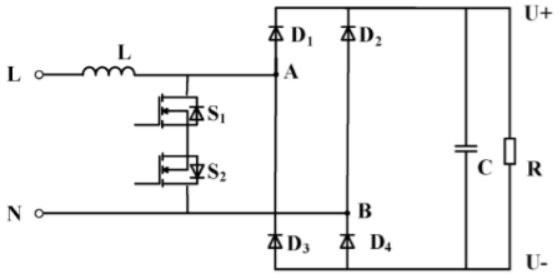
Active Bridge CCM PFC



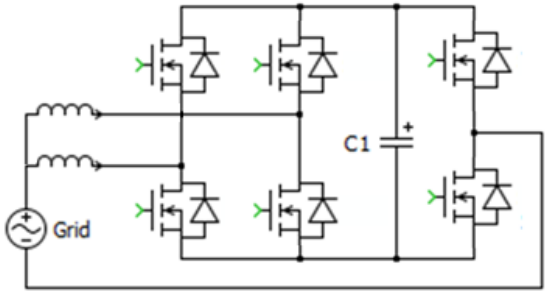
Totem Pole Semi-Bridgeless CCM PFC



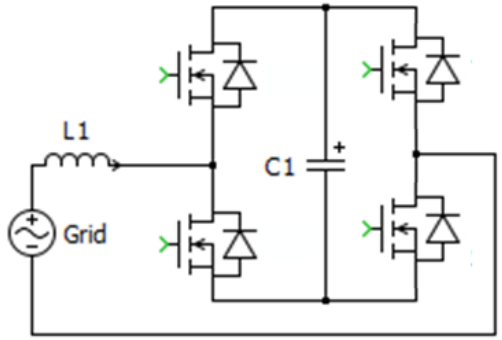
H Bridge PFC



CrM Interleave Totem Pole Bridgeless PFC



Totem Pole Bridgeless CCM PFC



- PFC topologies **before the adoption** of WBG device
- **Adopted** SiC devices

COMPARISON OF PFC SOLUTIONS

#	Topology	# PFC Choke	# of Power Switch	Power density	Peak Efficiency	Cost
1	Si Conventional CCM PFC	1	3*	Medium	98.3%	Low
2	Si Active Bridge CCM PFC	1	6	Medium	98.9%	Highest
3	Si Dual Boost Bridgeless PFC	2	6	Lower	98.6%	Medium
4	Si Dual Boost Bridgeless PFC SR	2	6	Lower	98.9%	High
5	Si H Bridge PFC	1	6	High	98.6%	Medium
6	Si CrM Totem Pole Bridgeless PFC	2	6	Medium	98.9%	Highest
7	SiC CCM Totem Pole Semi-BL PFC	1	4	Highest	98.8%	Medium
8	*SiC CCM Totem Pole bridgeless PFC	1	4	Highest	99.1%	High
9	GaN CCM Totem Pole Semi-BL PFC	1	4	Highest	98.8%	High
10	GaN CCM Totem Pole bridgeless PFC	1	4	Highest	99.2%	Highest
11	GaN CRM Totem Pole bridgeless PFC	2	6	Medium	99.1%	Highest

- SiC based CCM totem pole PFC can have higher efficiency and higher power density than Si based H-bridge PFC with similar or even lower cost.

EFFICIENCY COMPARISON OF PFC SOLUTIONS

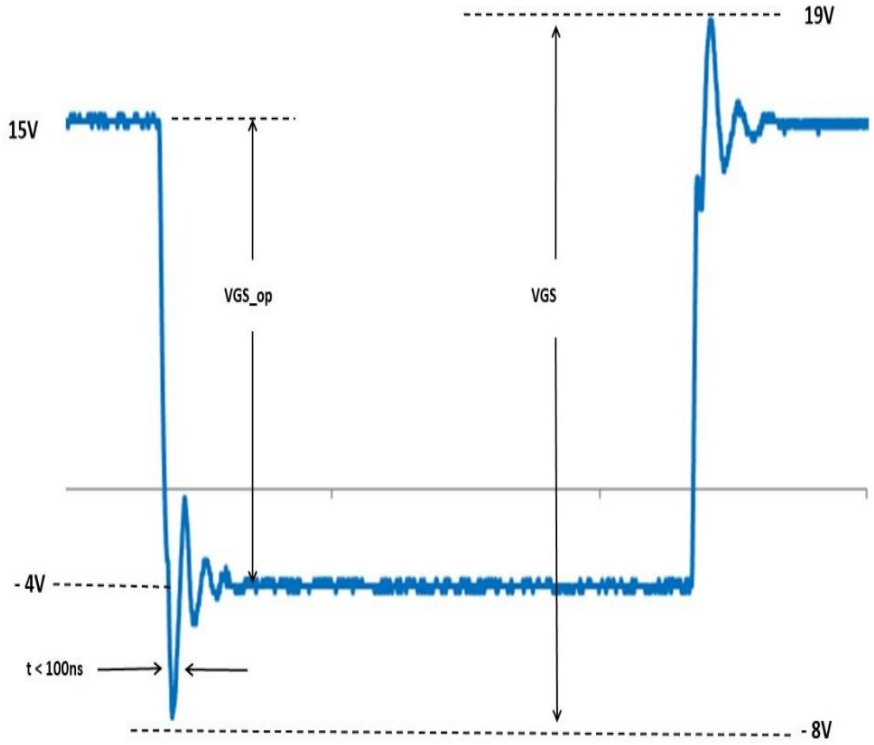
- SiC based CCM totem pole PFC can have higher efficiency than Si based H-bridge PFC.
- GaN has efficiency advantage at light load. But with much higher Rdson over temperature, the efficiency and power delivery capability is compromised at higher power.

→ SiC is the clear choice for the power components for Totem pole PFC especially for high reliability applications.

TIPS OF GATE DRIVING WITH SIC MOSFETS

GATE DRIVE VOLTAGE LEVEL

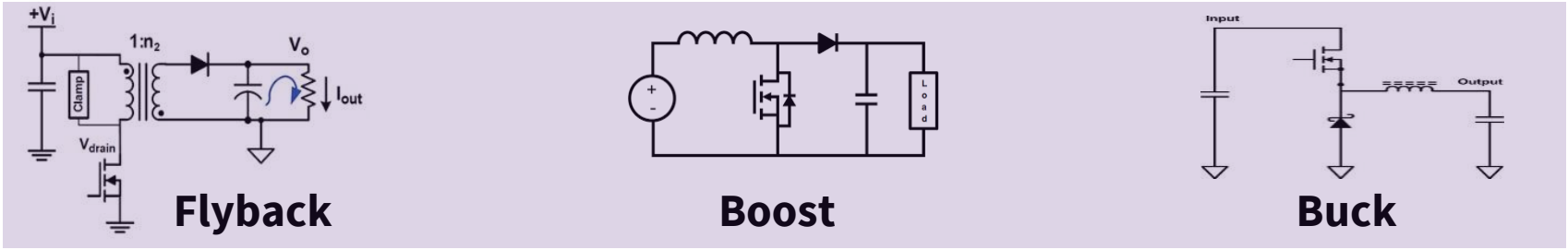
V_{GS}	Gate - Source voltage (Under transient events < 100 ns)	-8/+19	V	Fig. 29
V_{GS-op}	Gate - Source voltage (Recommended operating range)	-4/+15	V	



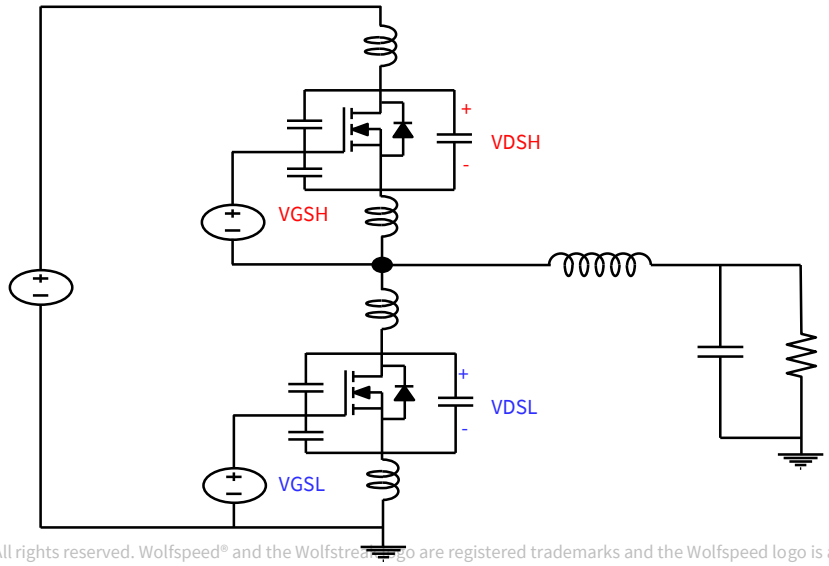
- The first $\mathbf{V_{GS}}$ rating is the absolute max rating. The max $\mathbf{V_{GS}}$ rating allows for ringing and overshoots that will be superimposed on top of the continuous gate drive voltage.
- The second $\mathbf{V_{GS\_OP}}$ rating is the recommended max operating setting for turn-on and turn-off voltage. The max nominal power supply voltage for turn-on is recommended at 15V, and -4V for turn-off. This is recommended value for safe operation and long term reliability.
- For nominal -4V, if considering tolerance +/-5%, the range is -4.2V/-3.8V. For very common -3V, the range will be -3.15V/-2.85V.
- For nominal +15V, if considering tolerance +/-5%, the range is 15.75V/14.25V.
- **Actually, if the layout is optimized, the negative gate bias can be -3V or -2V as long as there is no false turn-on. The benefit of using lower negative gate bias voltage is the Vf of body diode is lower.**

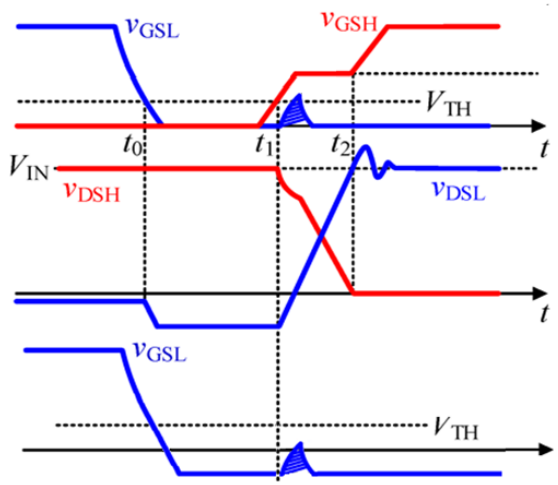
WHY NEGATIVE DRIVING VOLTAGE?

- Wolfspeed Gen3 SiC MOSFETs can safely operate at +15V/0V condition. Adding negative gate bias improves noise immunity, avoiding false turn-on in half bridge configuration.
- In single end power converter such as Flyback, Boost, or Buck converter, it is possible to use 0V turn-off voltage:



- It is recommended to use negative voltage for Totem Pole half bridge topology due to cross talk

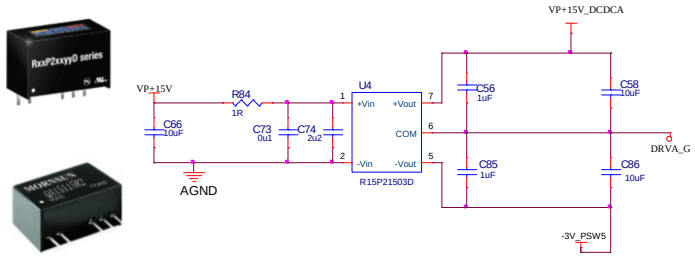




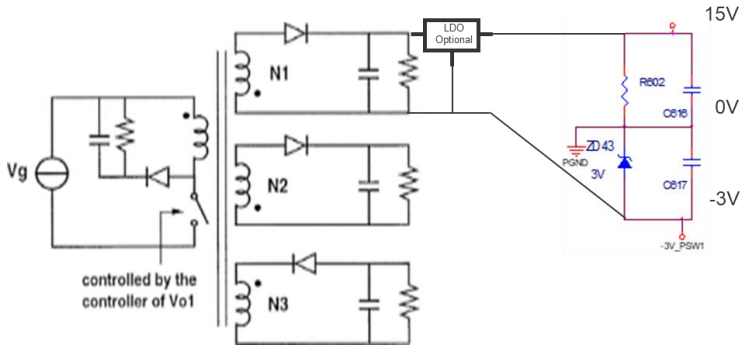
With negative Vgs

POSITIVE & NEGATIVE GATE DRIVER VOLTAGE SOLUTIONS

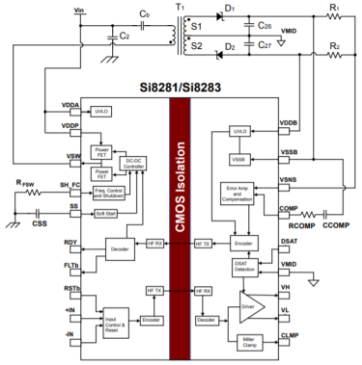
- OPTION **1** – Integrated solution
  - Dedicated +15V/-3V power supply



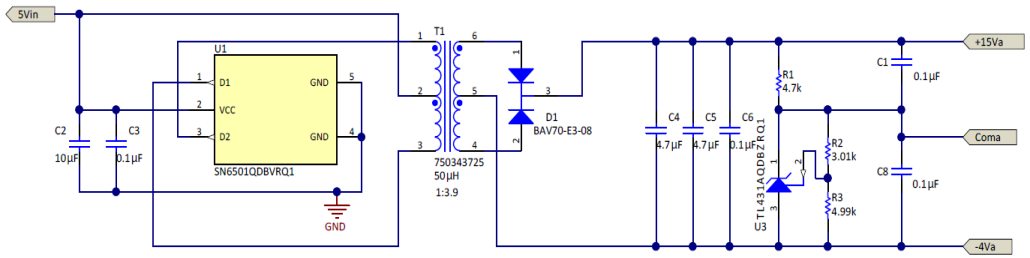
- OPTION **2** – Discrete solution
  - 18V multi-outputs Aux power supply. Generate -3V by resistor and Zener diode



- OPTION **3** – On board In the driver
  - Gate driver IC with built in DC/DC controller (e.g. Si8281)



- OPTION **4** – Build your own
  - Push-Pull Circuit from Texas Instruments TIDA-01605



DESIGN SUPPORT

Electrical simulation

https://www.wolfspeed.com/speedfit

LTspice®

plecs

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

WOLFSPEED KOREA CONTACT INFORMATION

- Sales: James Lee (이태훈 부장) james.lee@wolfspeed.com

- FAE: Daniel Ham (함정호 부장) daniel.ham@wolfspeed.com

We harness the power of Silicon Carbide to change the world for the better

Wolfspeed® Unleashing the Power of Possibilities™