SiC MOSFETs Enable Electric Vehicles with Enhanced Performance

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Outline

1. SiC technology
2. SiC Power MOSFETs
3. Traction inverter example: SiC MOSFET versus Si IGBT
4. Latest advances
5. Conclusion

SiC Technology

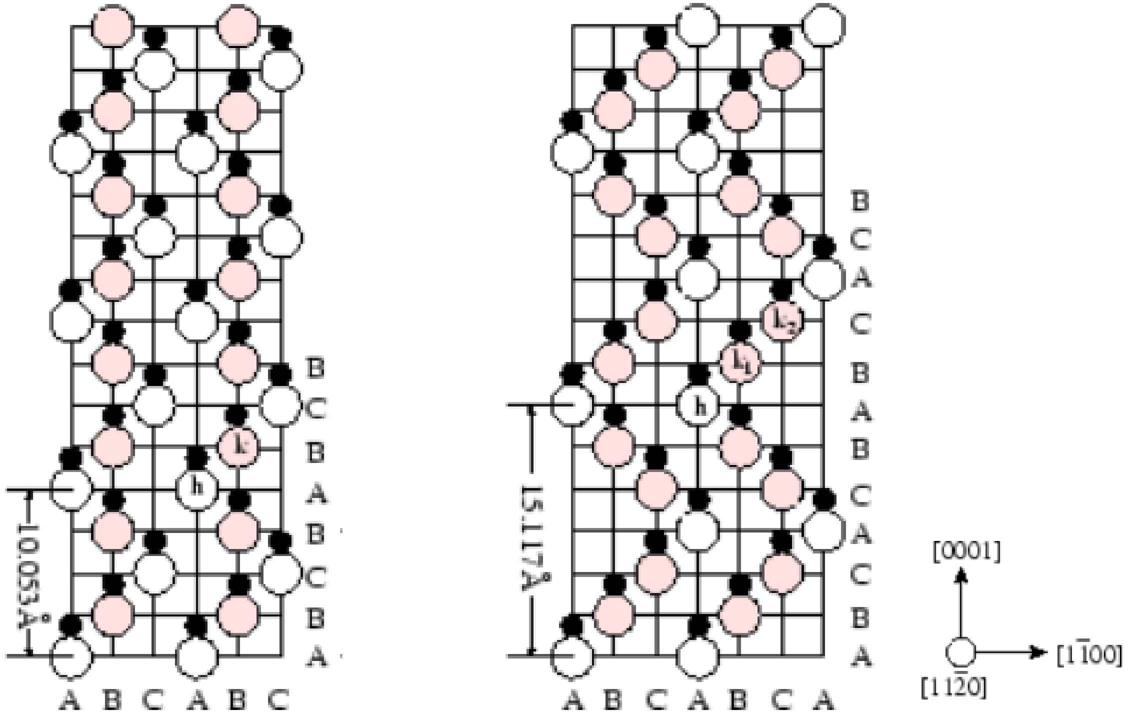
What is Silicon Carbide?

- 4H-SiC and 6H-SiC are both commercially available
- 4H-SiC is most important for power electronics

4H-SiC

- Is a wide bandgap semiconductor material
- Remains a solid up to 2830°C
- Is available in semiconductor grade wafers up to 6 inches in diameter

4H-SiC   6H-SiC



What makes 4H-SiC useful for Power Electronics?

- Can be doped both p-type and n-type
- High electron mobility
- SiO_2 is native oxide
- 3x higher thermal conductivity vs Si
- Large band gap energy allows very high temperature operation
- **High critical electric field, 10x that of silicon!**

Wide Bandgap Materials

Radical innovation for Power Electronics

	Si	GaN	4H-SiC
E_g (eV) – Band gap	1.1	3.4	3.3
V_s (cm/s) – Electron saturation velocity	$1x10^7$	$2.2x10^7$	$2x10^7$
ε_r – dielectric constant	11.8	10	9.7
E_c (V/cm) – Critical electric field	$3x10^5$	$2.2x10^6$	$2.5x10^6$
k (W/cm K) thermal conductivity	1.5	1.7	5

E_c → **low on resistance**

E_g → **low leakage, high Tj**

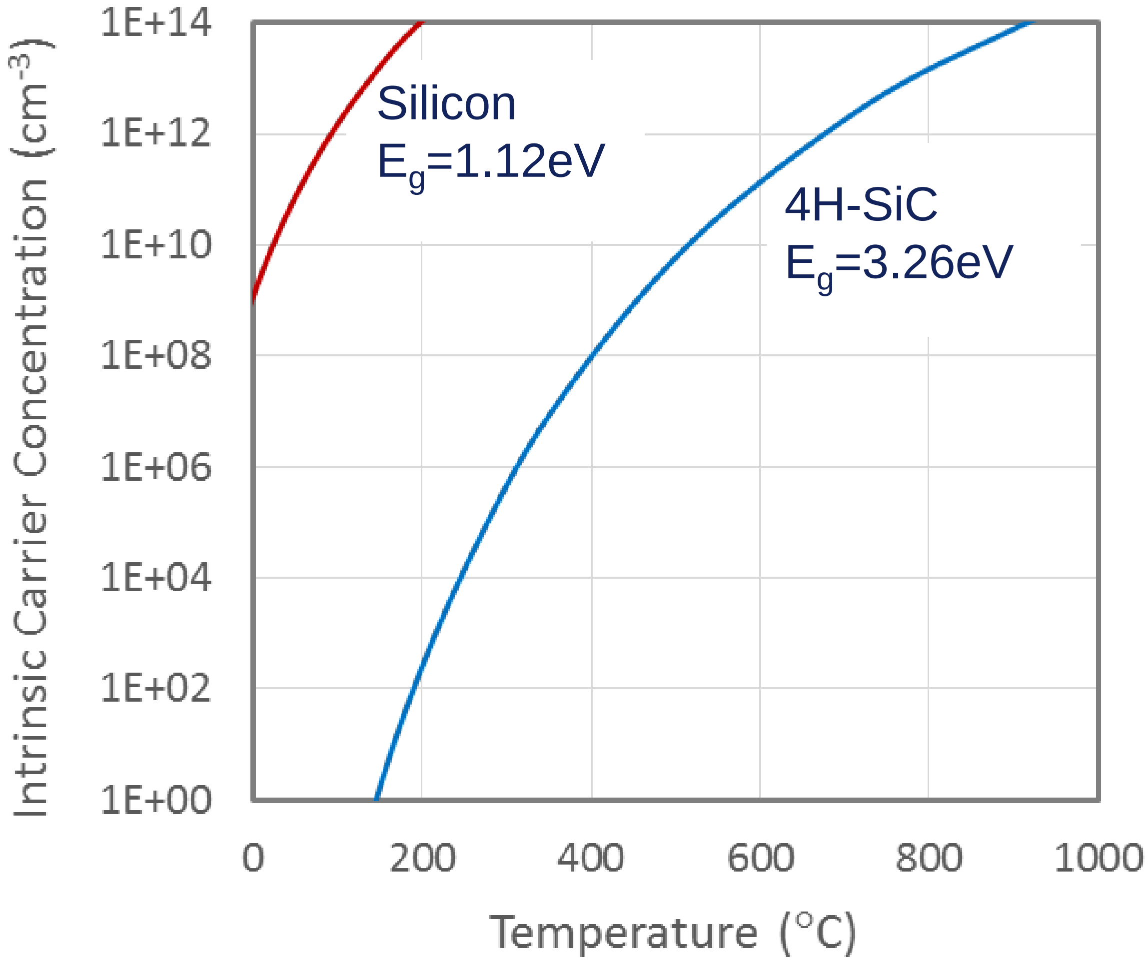
k → **Operation > 200 ˚C**
Reduced Cooling Requirements

V_s → **Higher switching frequency**
Lower switching losses

Intrinsic carrier concentration, n_i

SiC vs. Silicon

- Intrinsic carriers are thermally generated and increase in number at higher temperatures
- Because of its larger band gap energy, SiC maintains low intrinsic carrier concentration up to 900°C



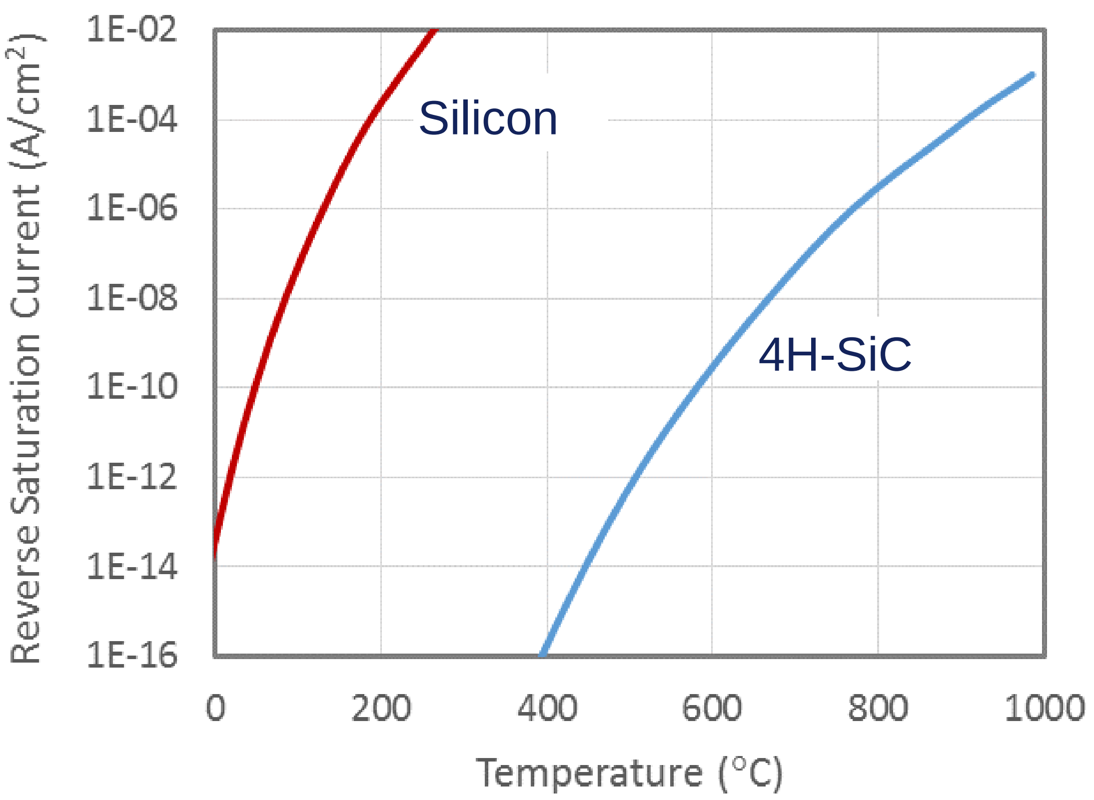
SiC provides low reverse leakage current up to high temperature

Reverse saturation current of a p⁺n diode:

$$J_S = q\, n_i^2 \left(\frac{1}{N_D} \sqrt{\frac{D_p}{\tau_p}} \right)$$

- Silicon becomes unusable above ~ 250°C due to high leakage current
- 4H-SiC has low reverse leakage current up to 900°C

Reverse saturation current for 1200V p⁺n diode

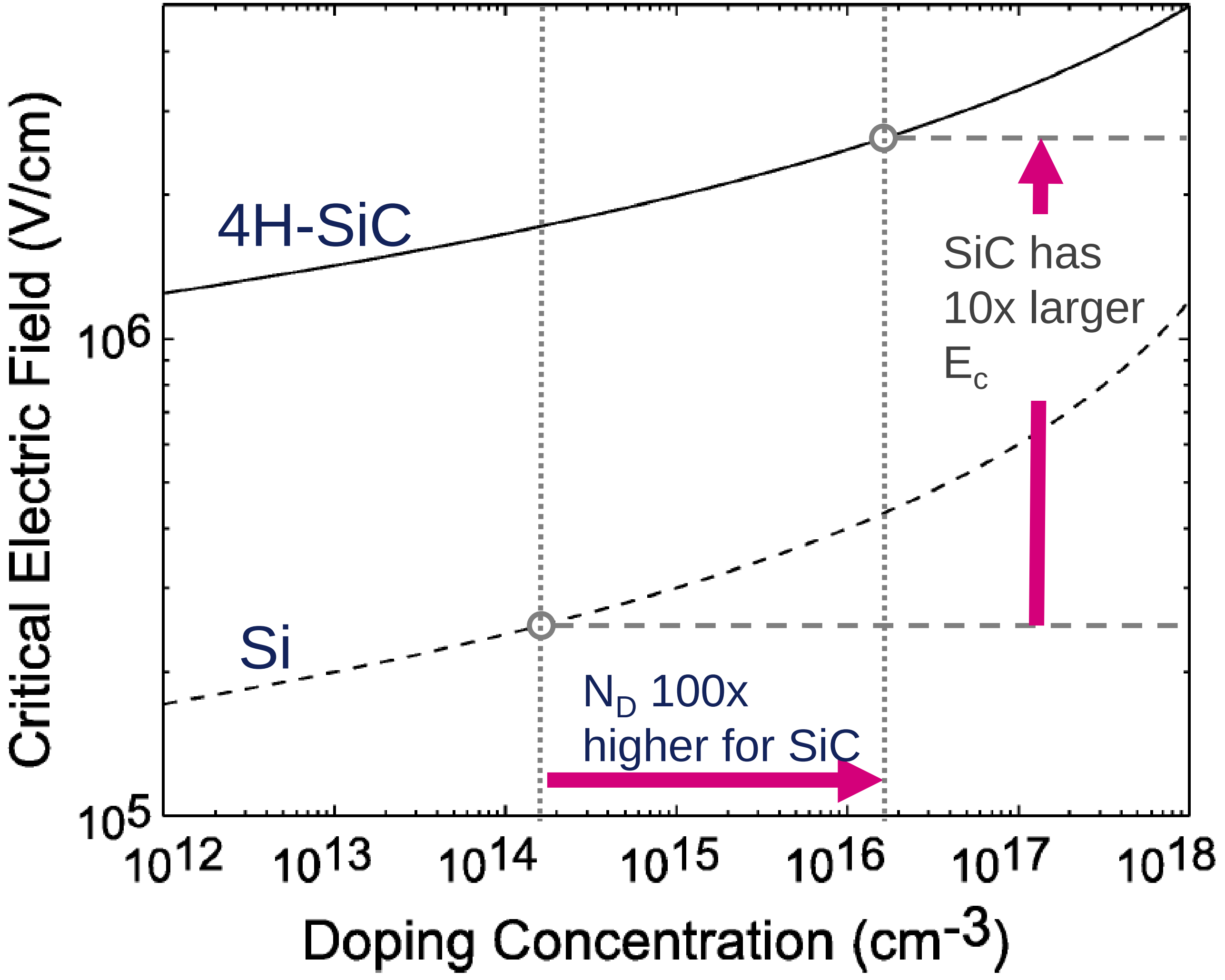


Critical electric field

- For a given breakdown voltage, the larger critical electric field of SiC enables much higher drift layer doping vs Si

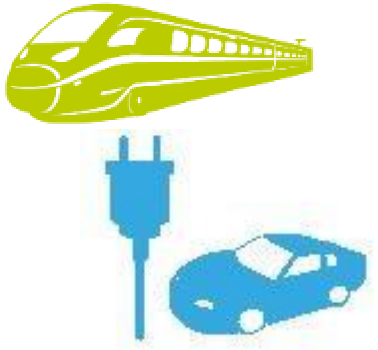
Material	Drift layer doping for BV=1200V
Si	1.5e14 cm^{-3}
SiC	1.6e16 cm^{-3}

Critical electric field vs n-drift layer doping concentration



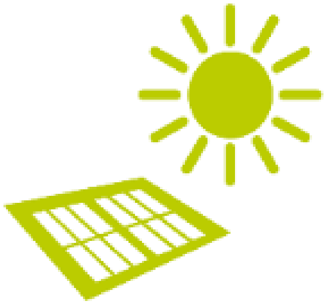
Note: circles show N_D required for 1200V NPT design

Key Applications for SiC



HEV/EV & Traction

SMPS & PFC

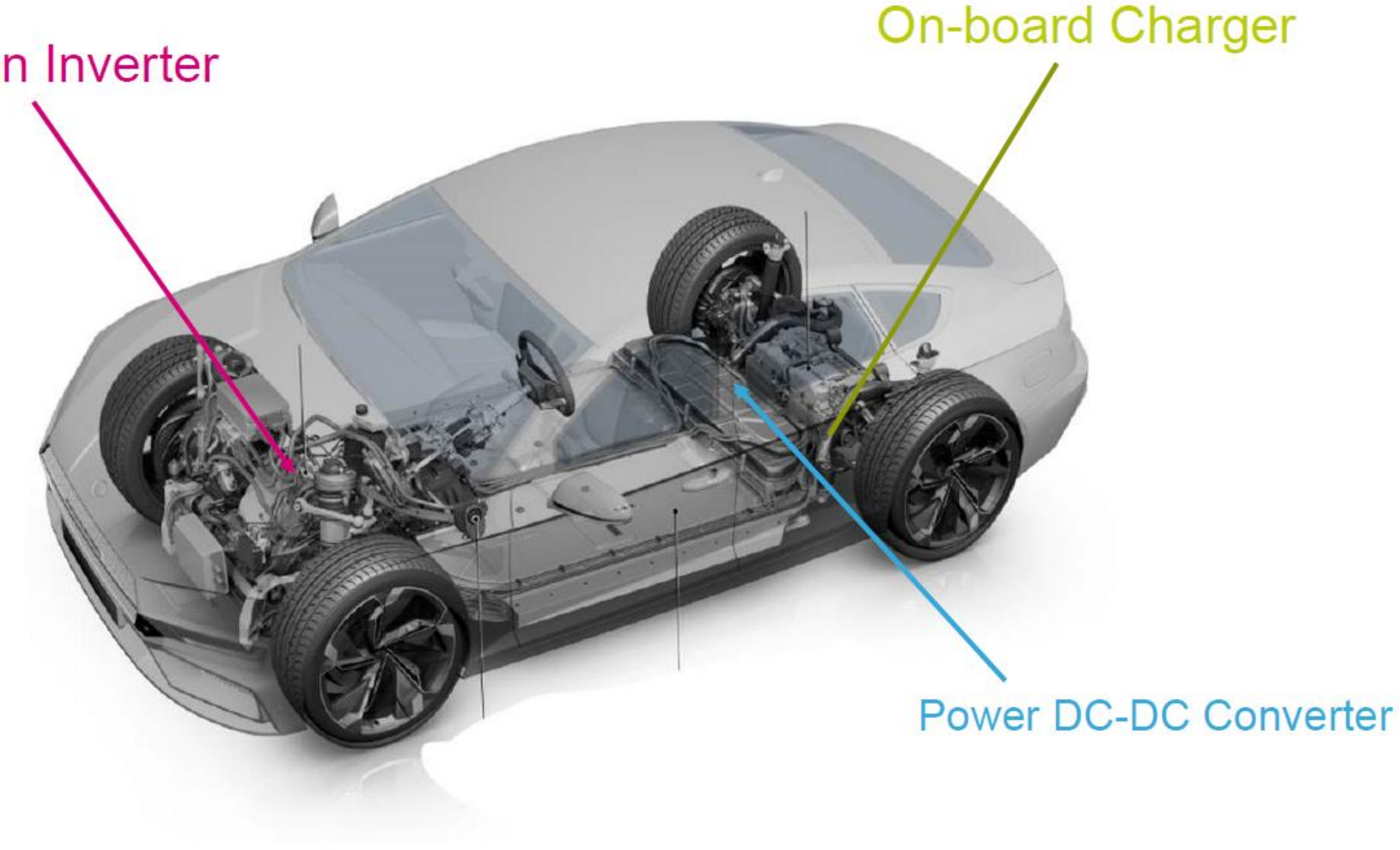


Solar Inverter

OBC & Charging station

Industrial Drives

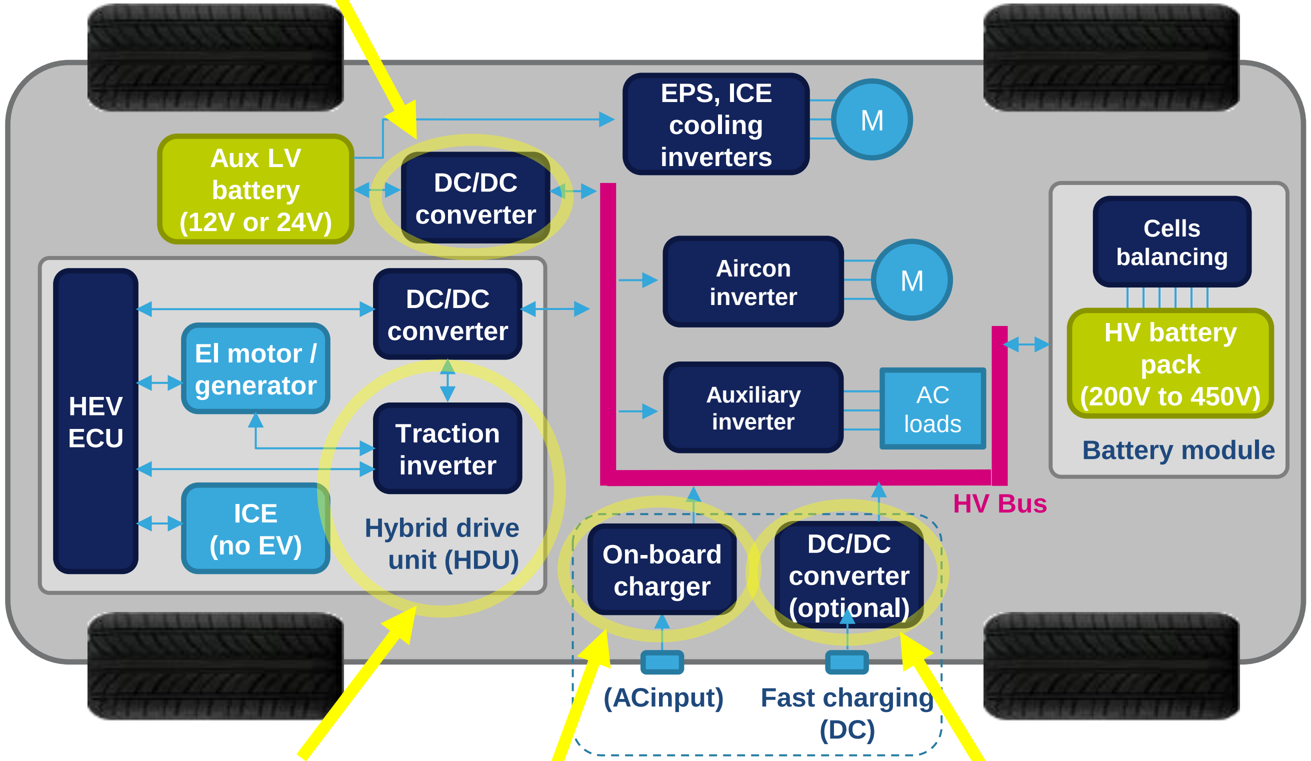
Where is Silicon Carbide Being Used
in Electric Vehicles?



e-Vehicle block diagram

HEV/EV

Output Power: **4kW**
IGBT → SiC MOSFET
50kHz – 200kHz



Silicon content

Mechanical or electro-mechanical

Batteries

Output Power (EV): **80kW — 250kW**
IGBT → SiC MOSFET
12kHz and higher

Output Power: **20kW**
SiC MOSFET/SiC SBD
50kHz – 200kHz

Output Power: **50kW**
Si MOSFET → SiC MOSFET
50kHz – 200kHz

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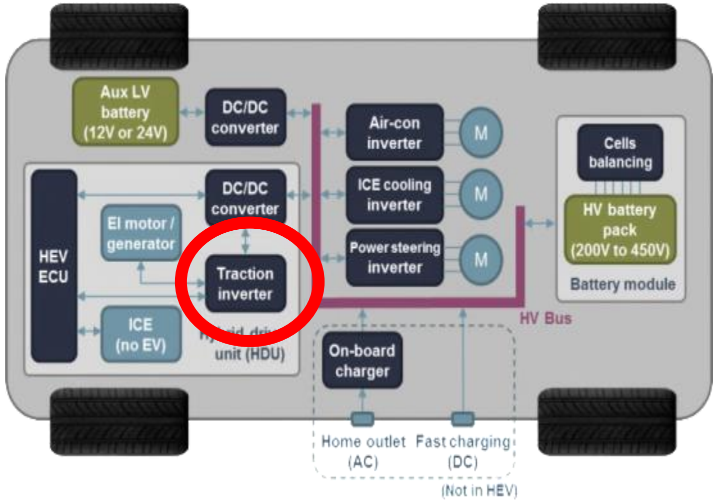
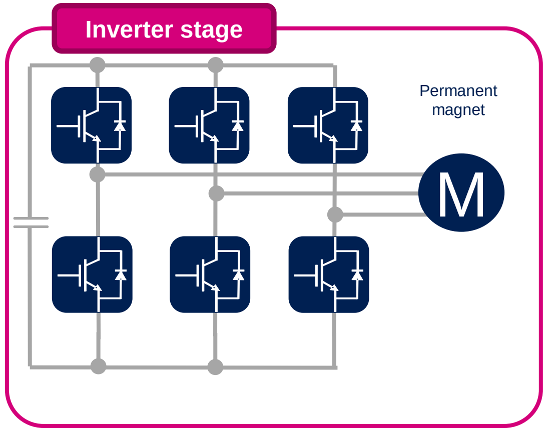
Main inverter for HEV/EV

- **Usually 3-phase permanent magnet motors are used for traction**
- **Operating voltage from 48V to 800V**
- **Bi-directional**
  - Feed the electric motor when driving the wheels
  - Stream energy back to HV bus when breaking vehicle
- **Nominal power ranging from 10kW (ICE assistance) to 250kW (pure EV)**





For bus up to 400V → SiC MOS 650V

For bus in the range [400V-800V]→ SiC MOS 1200V

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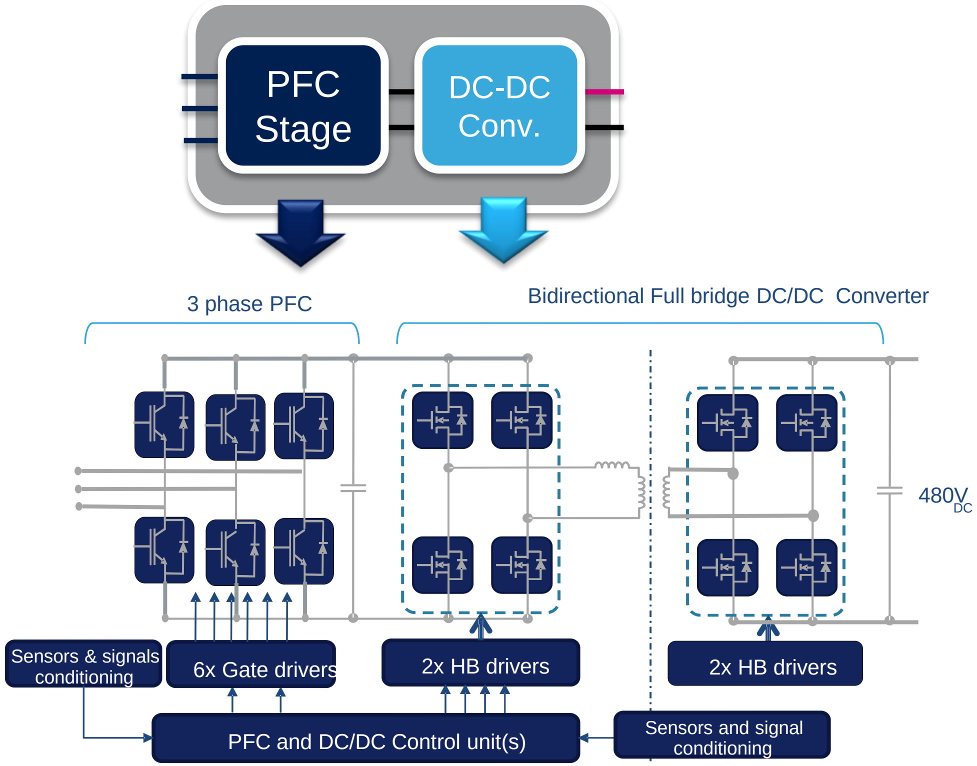
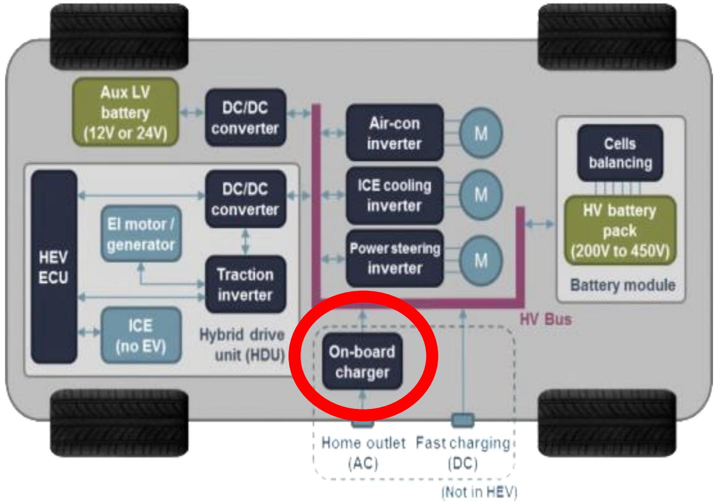
Battery charger for HEV/EV





Single-phase architecture→ SiC MOS 650V

Three-phase architecture→ mainly SiC MOS 1200V

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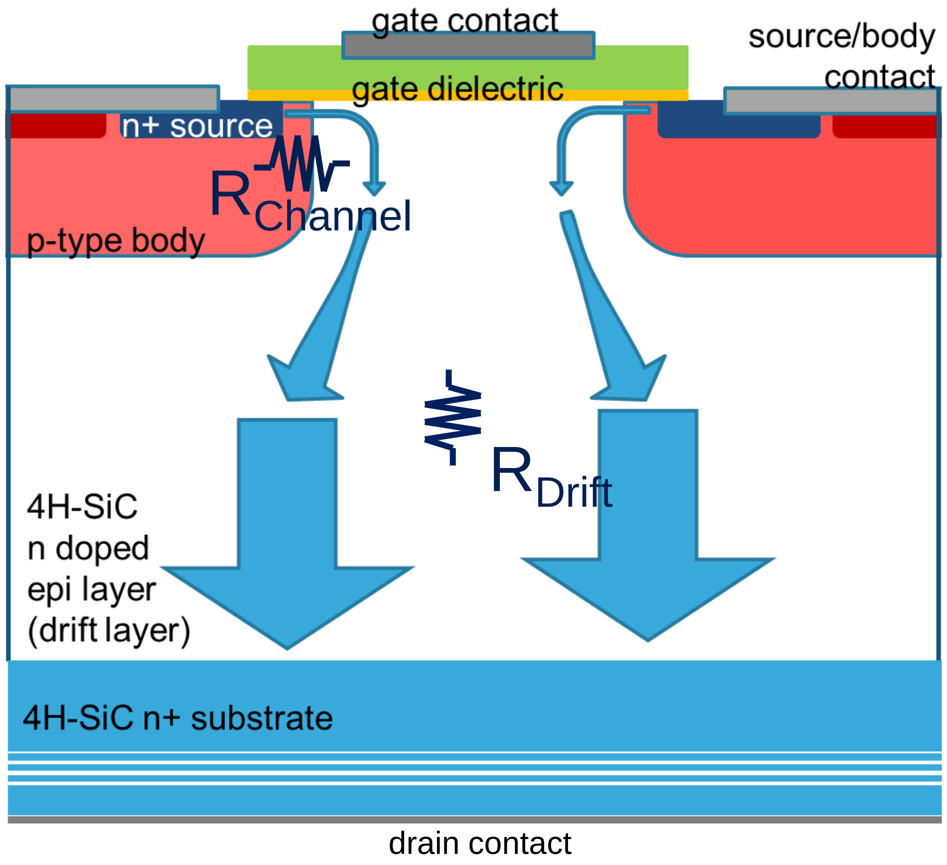
SiC Power MOSFETs

High-Voltage DMOSFET Structure



$R_{DS(on)}$ is determined mainly by R_{Drift} and to lesser extent $R_{Channel}$

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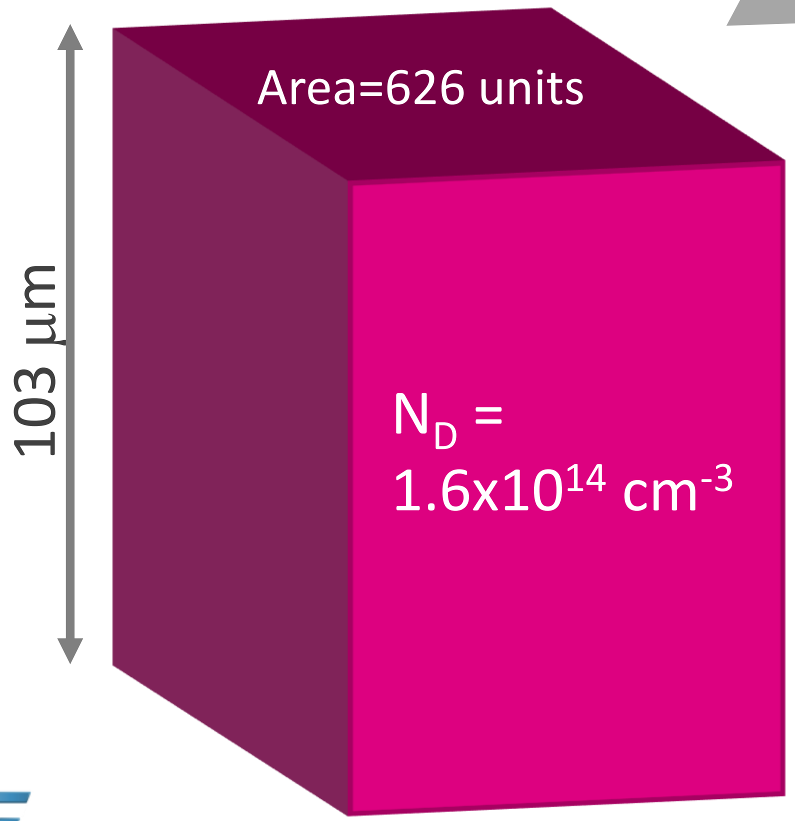
Drift layer dimensions for 1200V DMOSFET

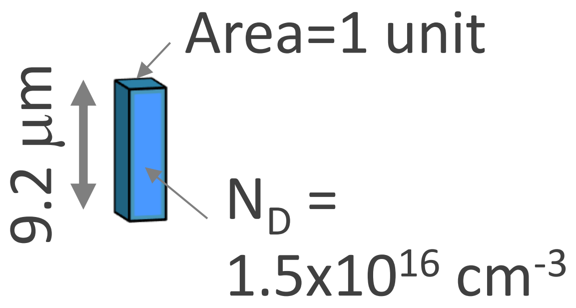
SiC vs. Silicon

Silicon

for columns of equal resistance

SiC





For equal drift layer resistance at T_j=25C:

$$\text{AREA: } \text{SiC} = \frac{1}{626}\text{ Silicon}$$

$$\text{THICKNESS: } \text{SiC} = \frac{1}{11}\text{ Silicon}$$

$$\text{CAPACITANCE: } \text{SiC} = \frac{1}{46}\text{ Silicon}$$

$$\text{THERMAL RESISTANCE: } \text{SiC} = 17\text{ Silicon}$$

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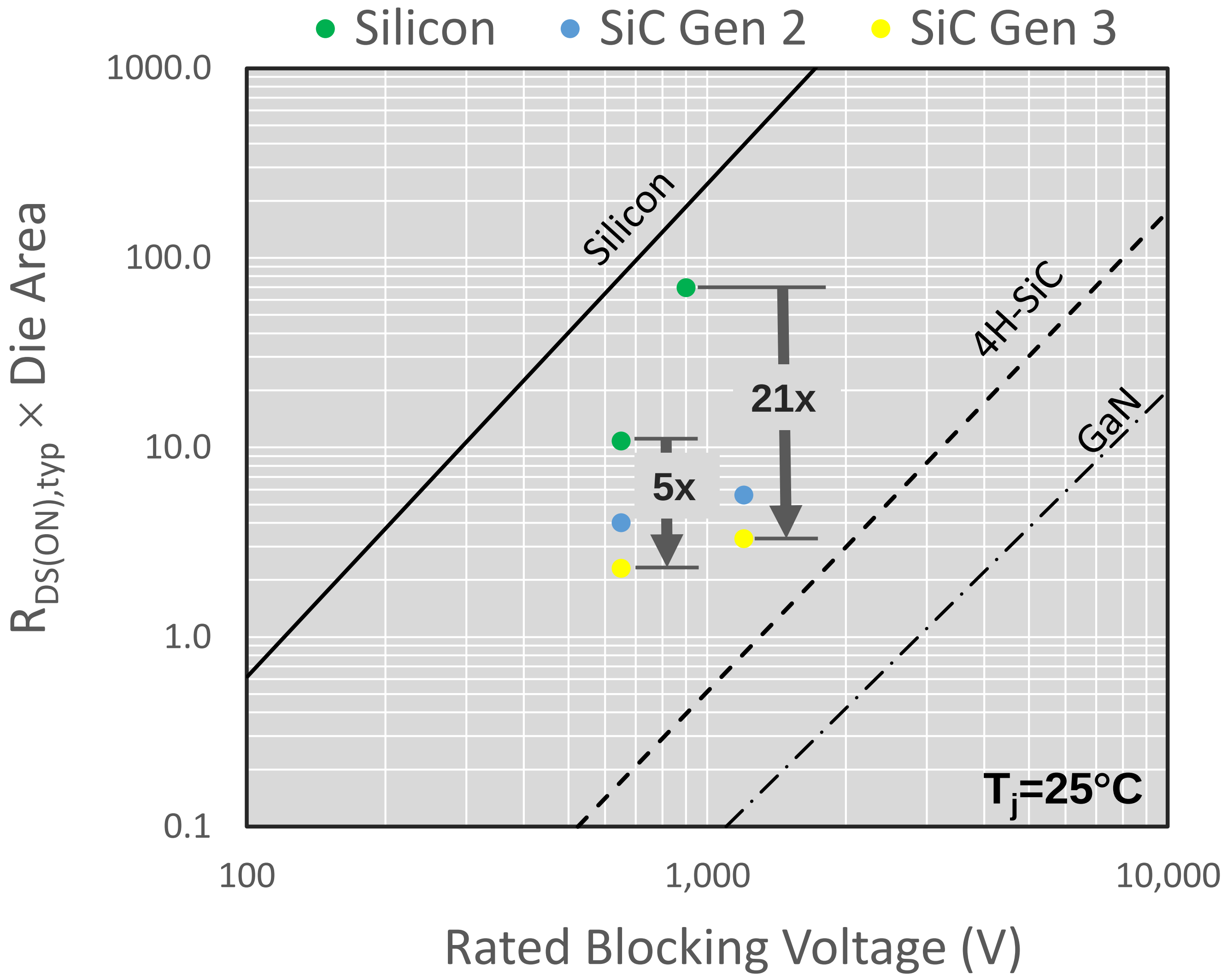
SiC offers dramatic reduction in device footprint!

MOSFET $R_{DS(on)}$ x Area Figure of Merit



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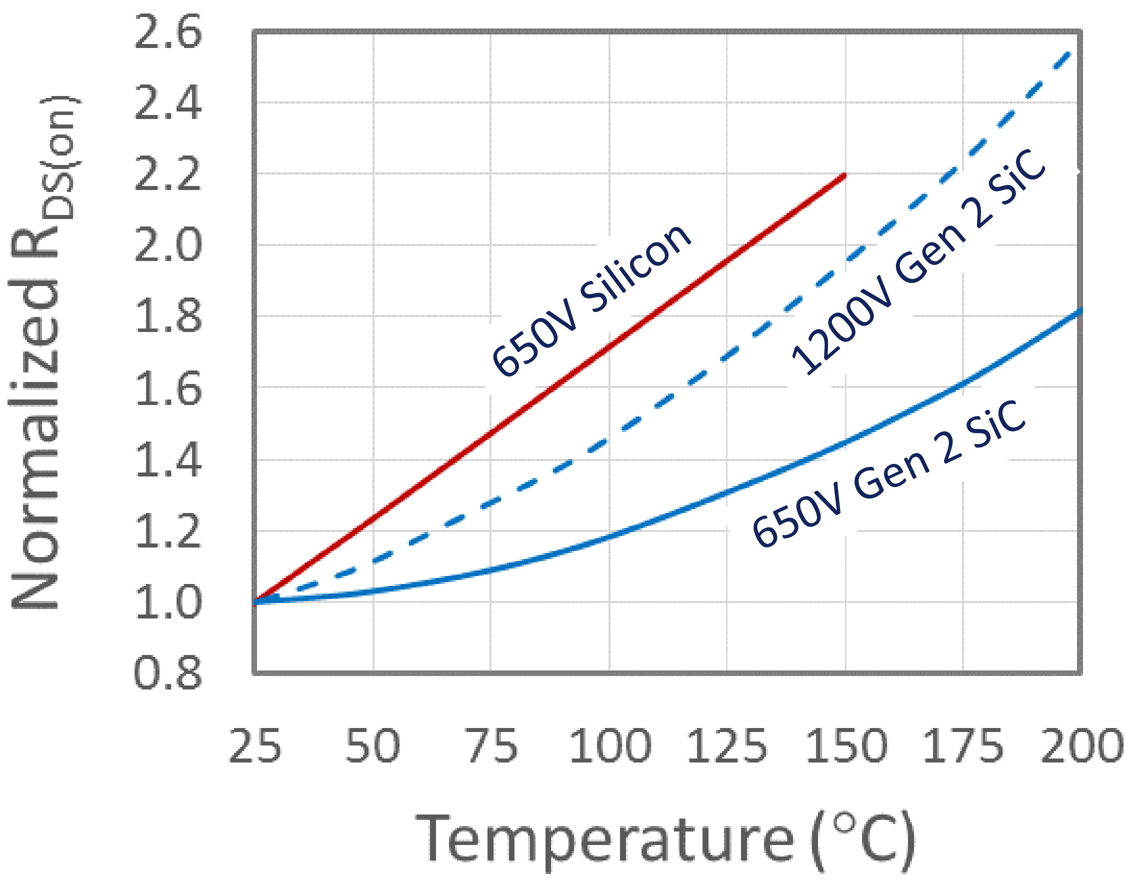
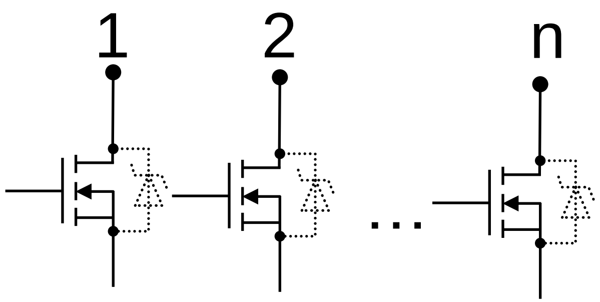
$R_{DS(on)}$ variation with temperature

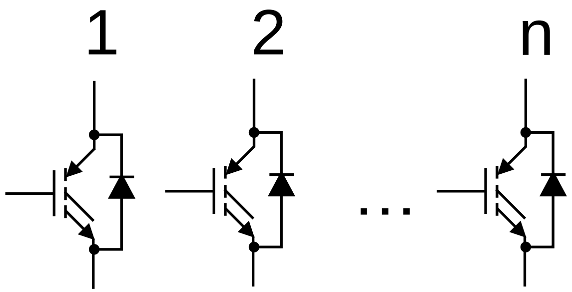


ST is the only supplier to guarantee max T_j as high as 200°C in plastic package

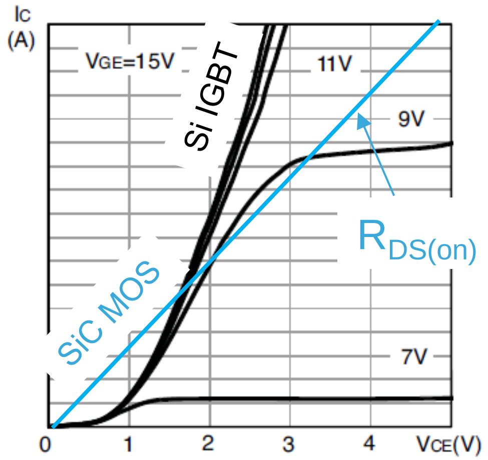
SiC MOSFET Allows Lowest Conduction Losses



When "n" MOSFETs are paralleled the total $R_{DS(on)}$ is divided by "n" allowing very low conduction losses

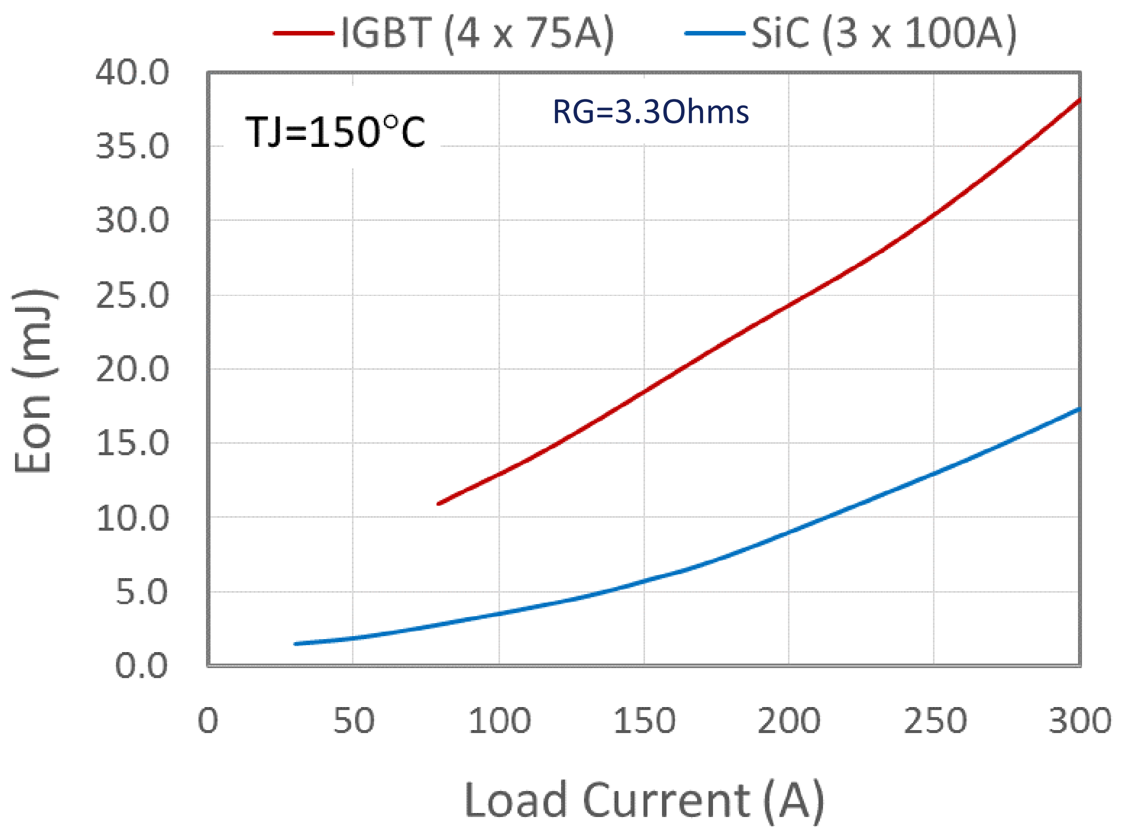


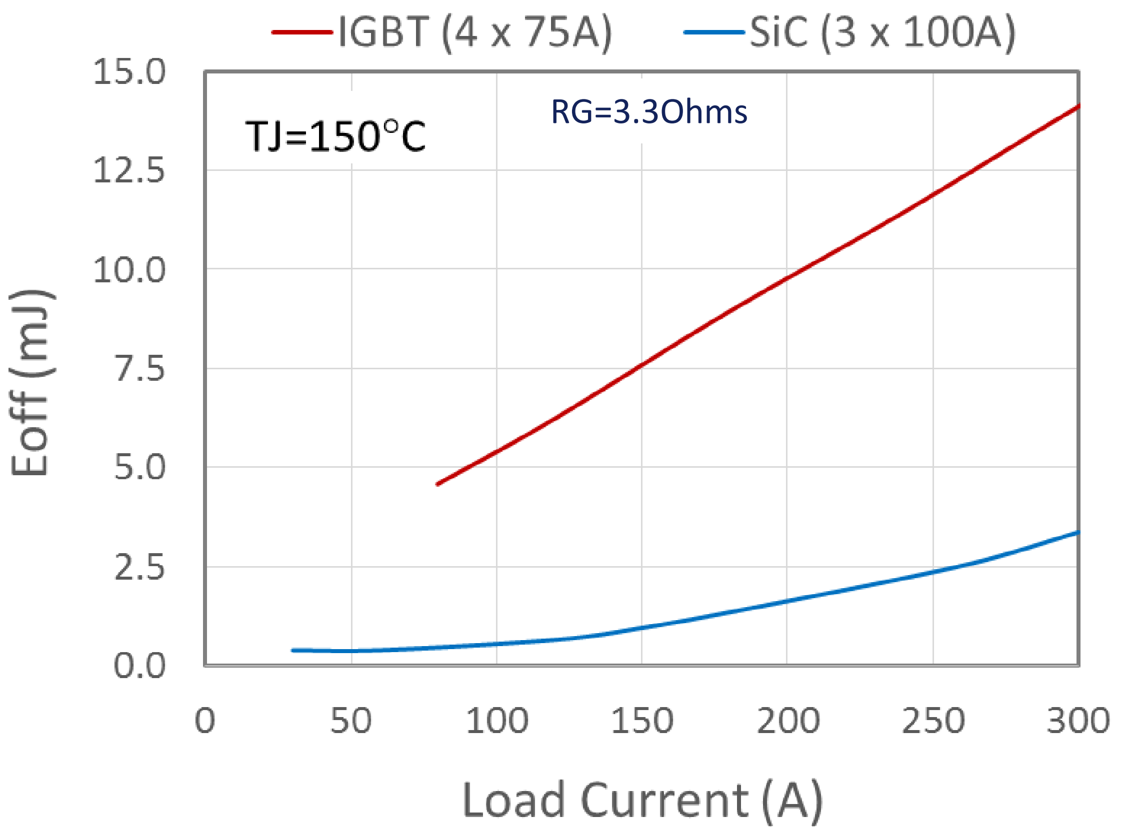
When "n" IGBTs are paralleled the $V_{ce(sat)}$ doesn't decrease linearly but reaches a limiting voltage drop of about 0.8V as n increases.



Switching energies for 1200V rated devices

IGBT vs SiC MOSFET





IGBT: 4 x [Competitor IGBT+Diode, co-packaged] (1200V, 75A, 46+23 mm^2 per package)
SiC MOSFET: 3 x SCT110N120G3D2AG (1200V, 100A, 26 mm^2 per die)

Benefits of SiC MOSFETs

Key Benefits

Extremely low Switching Losses and Ultra-Low $R_{DS(on)}$

Higher operating frequency for smaller and lighter systems

Good Thermal Performance

High operating temperature (T_{jmax} = 200°C)
Reduced cooling requirements & heat-sink, Increased lifetime

Easy to Drive

Fully compatible with standard Gate Drivers

Very fast and robust intrinsic body diode

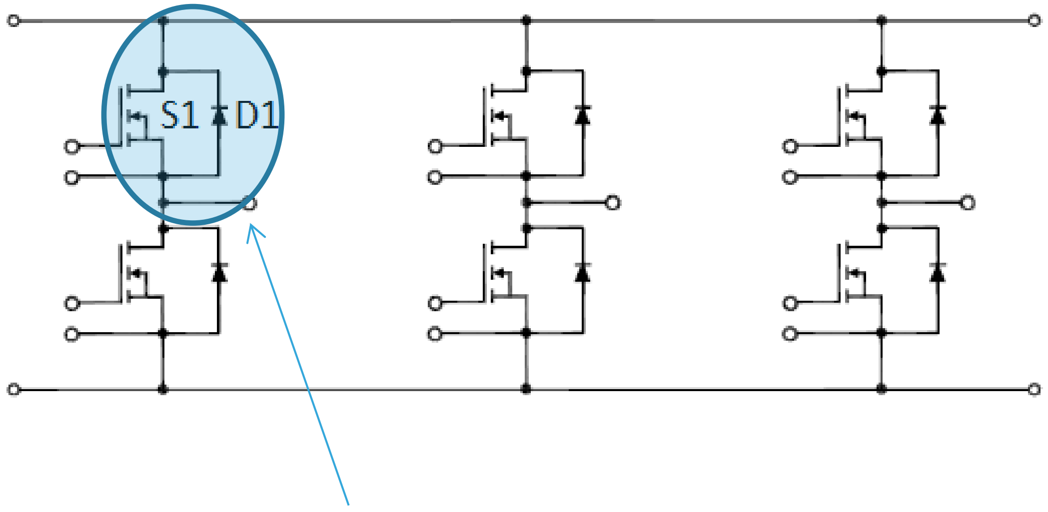
Separate antiparallel diode not required

80kW EV Traction Inverter Power Loss Estimation:

1200V Gen 3 SiC MOSFETs vs 1200V Si IGBT + Diode

Operating conditions

- Topology: Three phase inverter
- Bipolar PWM Strategy
- Synchronous rectification (SiC version)
- DC-link voltage: 800V_{dc}
- Current 250Arms (peak) 120Arms (nom)
- Switching frequency: 16kHz
- V_{gs}=+18V/-5V for SiC, V_{ge}=±15V for IGBT
- Cos(phi): 0.8
- Modulation index (MI): 1
- Cooling fluid temperature: 65℃
- $R_{thJ-C(IGBT-die)}$=0.19℃/W;
  $R_{thJ-C(SiC-die)}$=0.30℃/W
- $T_j \leq 80\%*T_{jmax}$℃ at any condition



Si IGBT requires antiparallel diode, SiC MOSFET does not

Switch (S1+D1) implementation

4 x 1200V, 75A IGBTs + 4 x 1200V,75A Si diodes
vs.
3 x 1200V, 100A SiC MOSFETs SCT110G3D2AG

Power loss at peak condition

fsw=16kHz, 250A_{rms} (10sec)

* Typical power loss values

Loss Energy	Si-IGBT + Si-diode Solution	Full-SiC Solution
Total chip-area	180 mm² (IGBT) + 90 mm² (diode)	78 mm²
Conduction losses* (W)	196.2	256.1
Switching losses* (W)	316.6	94.0
Diode's conduction losses* (W)	58.3	49.0
Diode's Q_{rr} losses* (W)	91.1	6.4**
(S1+D1) Total losses* (W)	**662.2**	**405.6**
Junction Temperature (℃)	**134.2**	**151.5**

SiC vs Si per switch (S1+D1)

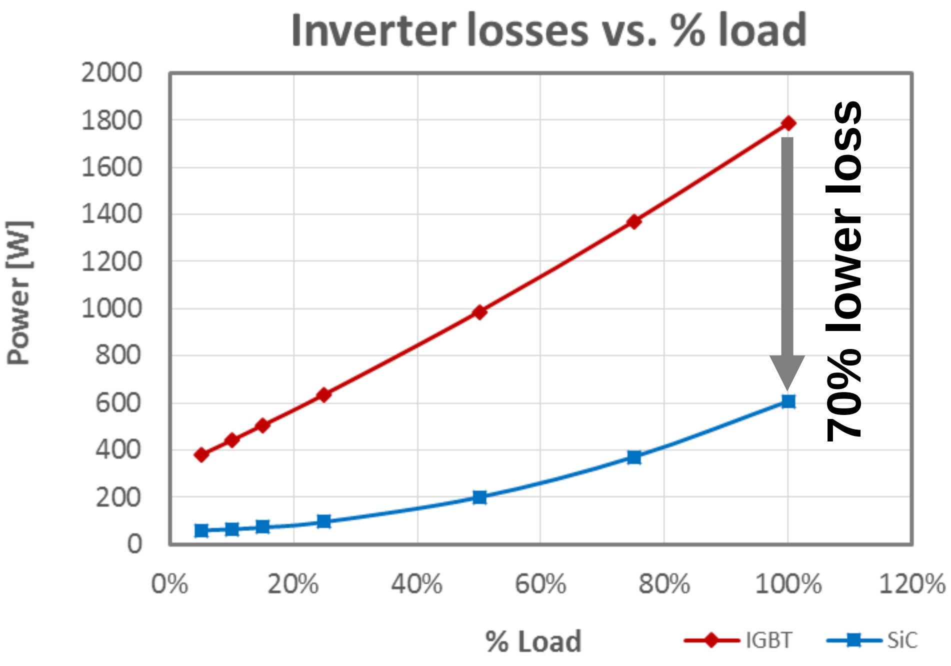
- Total chip-area: 3.5x smaller area
- Switching losses: 3.4x lower
- Total losses: 40% lower
- Junction temperature: T_J < 80% T_{jmax}

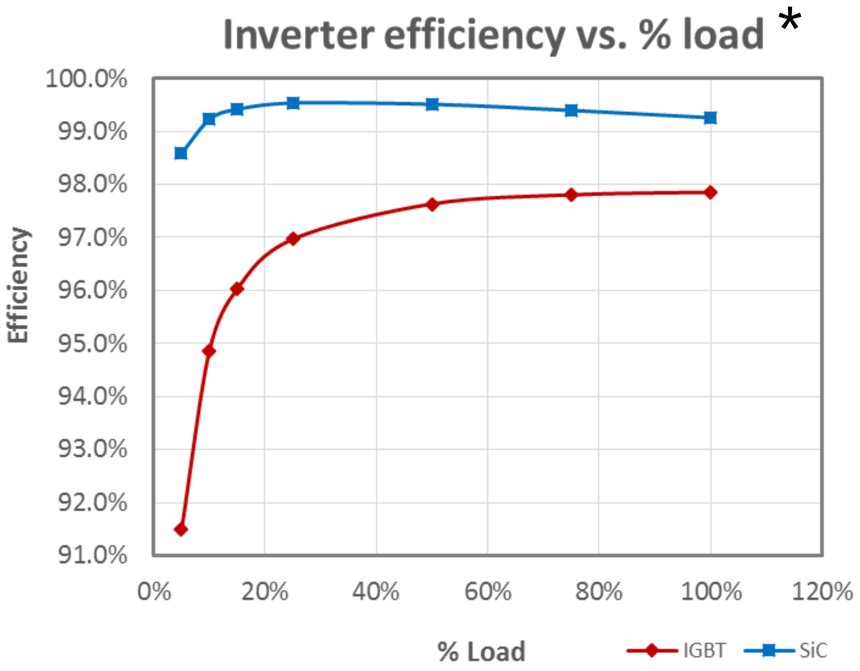
** Assuming di/dt = 2000 A/µs at I_{SD}=50A

SiC MOSFET runs at higher junction temperature in spite of lower losses. This is due to the exceptional SiC R_{DSON} x Area FOM.

SiC Solution: lower losses, higher efficiency

f_{sw}=16kHz, 100% load: 120A_{rms} (80kW)





SiC shows much lower loss over the whole load range

SiC offers 1.4% higher efficiency or more over the whole load range!

Lower losses mean smaller cooling system and longer battery autonomy

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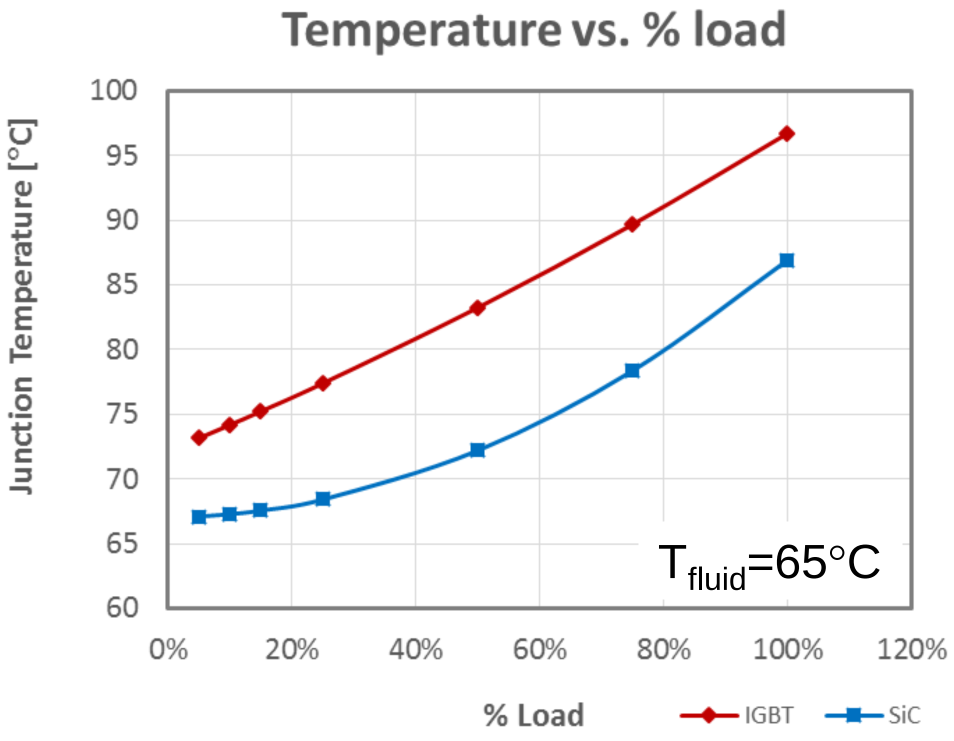
* The simulated efficiency takes into account only the losses due to the switches and diodes forming the bridge inverter

Remarks about junction temperature

f_{sw}=16kHz, 100% load: 120A_{rms} (80kW)



- $R_{th,JC(IGBT\text{-}die)}$=0.19℃/W
- $R_{th,JC(SiC\text{-}die)}$=0.30℃/W

Heat sink:

- $R_{th,CA}$=0.35℃/W

SiC solution is better than Silicon in reliability since SiC has lower $\Delta(T_j - T_{fluid})$ up to 100% load.

SiC MOSFET enables EV cost savings

Battery cost savings

- SiC inverter is 3.4% more efficient vs. IGBT inverter at average EV operating condition (15% load)
- Compared to IGBT based EV with 85kWh battery, SiC version requires only 82.1kWh for same range
- Typical battery cost: $150 per kWh
- **Battery cost savings with SiC based inverter (this example) : $435**

Heat sink considerations

Heat sink must be sized according to power dissipation at maximum operating condition

Inverter dissipation at peak load (250Arms):

	IGBT	SiC MOSFET
Power Dissipation	3973W	2434W

SiC based inverter will only need to dissipate **61% of the heat** compared to IGBT version

➔ **SiC MOSFET allows smaller, lower cost heatsink**

SiC MOSFET traction inverter

Key advantages

- More than 50% module/package size reduction
  - Much smaller semiconductor area giving ultra-compact solution
- >1.4% efficiency improvement and 70% lower loss at full load:
  - Much lower loss at low load allows smaller battery for same range
- 40% cooling system downsize:
  - Lower losses at full load giving smaller cooling system
  - Lower ΔT (T_j-T_{fluid}) in the whole load range giving better reliability

Latest advances:

- new discrete power package
- advanced isolated gate driver

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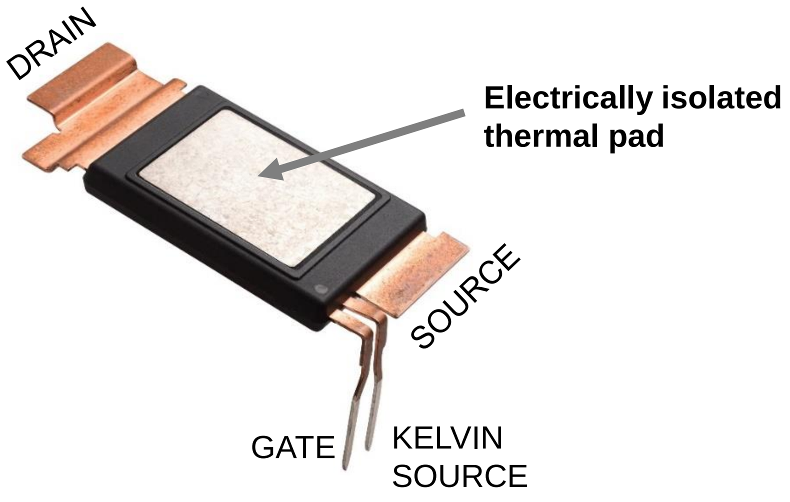
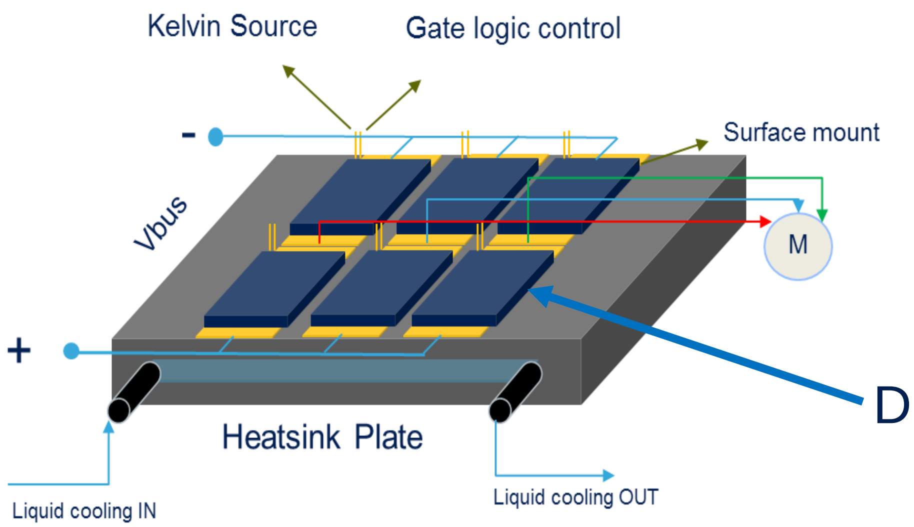
STPAK^{TM}: Multi Sintering Package

Ideal for Electric Vehicle applications





Direct sintering to the bottom of the heatsink

- Multi sintering solution for better thermal performance and higher reliability
- Low inductance connection to bus bar
- Kelvin source pin
- AEC-Q101 qualified, 175°C Maximum T_j
- Suitable for both SiC MOSFET and IGBT
- 650V and 1200V rated

STGAP1AS: advanced galvanically isolated gate driver

AEC-Q100

Wide operating range (T_A -40°C to +125°C)

5 A sink/source current

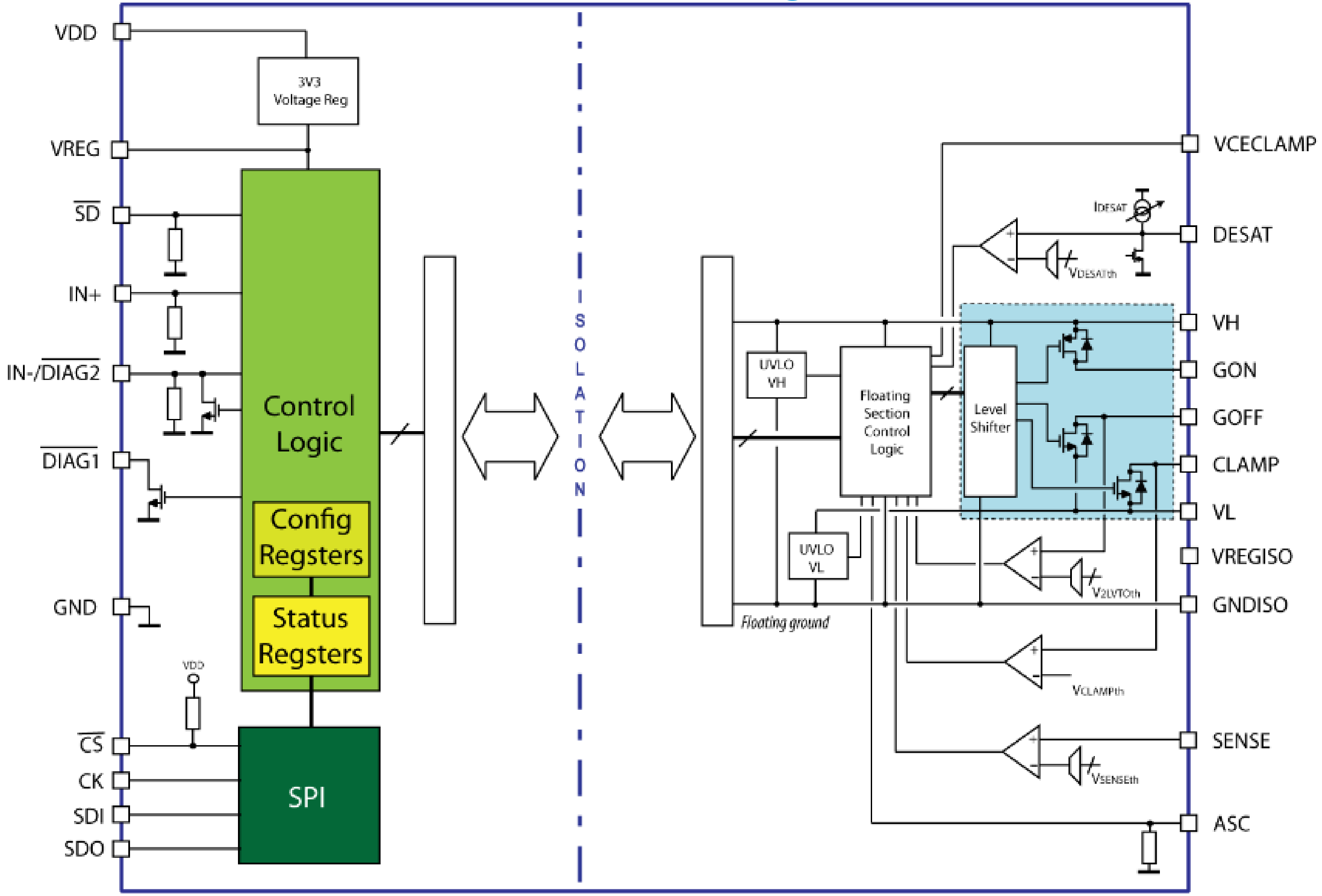
High Voltage Rail up to 1.5 kV
Wide drive voltage range (+ 36 V / -10V)

Short propagation delay
100 ns typ.; 130 ns max over temperature

Excellent CMTI rating
50 V/ns across full temperature range

Advanced features
5A Active Miller clamp, Desaturation detection, 2-level turn-off, VCEClamp, ASC

STGAP1AS Block Diagram



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Conclusions

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Conclusion

- SiC MOSFET-based power converters now offer system level benefits compared to silicon IGBT-based solutions
  - Traction inverter example shows how SiC can improve reliability and reduce system level cost
- SiC MOSFETs provide reduced footprint today compared to silicon based solutions and further footprint reductions are still possible
- Higher volume use and further innovation of SiC will continue to push down the cost and further displace silicon power transistors in the future

Thank You!

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