Benefits of Applying Silicon Carbide Power Devices

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Technology Tour 2019

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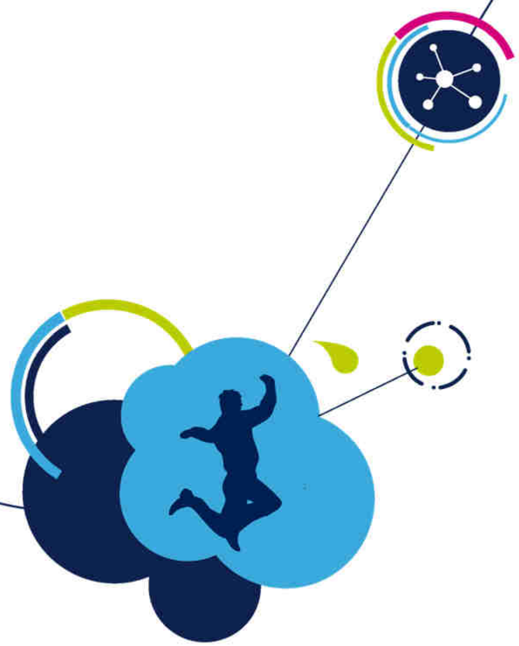
Agenda

Time	Presentation	Speaker
10:30	SiC Technology	Jeff Fedison
	SiC Power MOSFETs	
	SiC Shottky Diodes	
	Overview of EV/HEV Power Electronics	
	EV Traction Inverter Design Example	
12:00	Conclusion	



SiC Technology

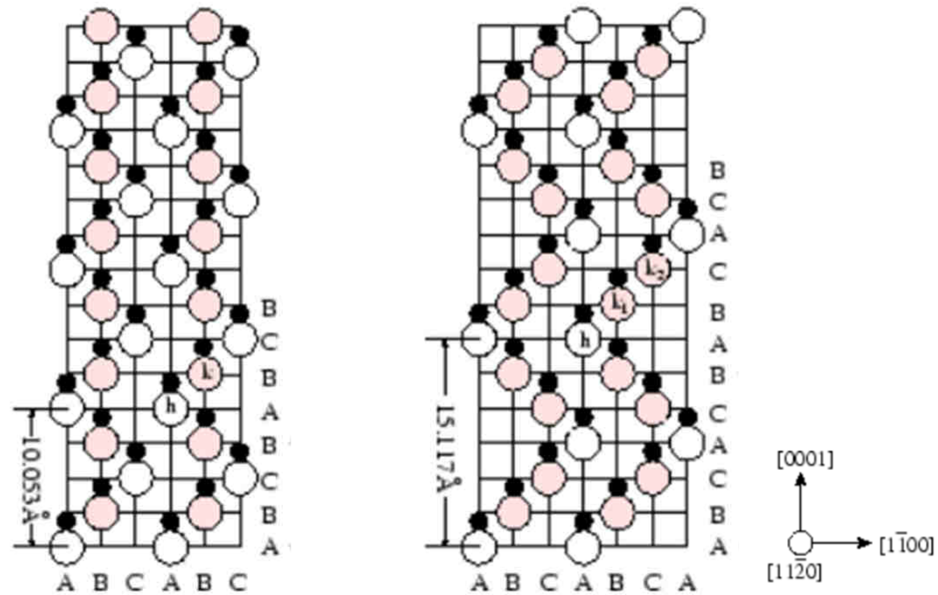
What is Silicon Carbide?

- 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

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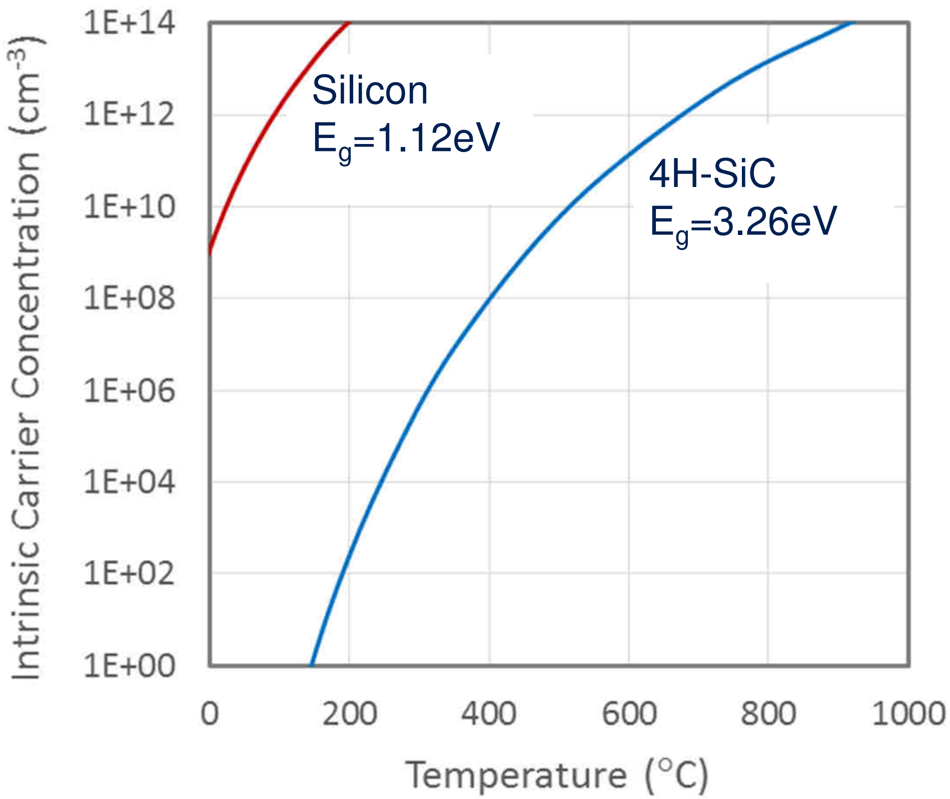
Intrinsic carrier concentration, n_i

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



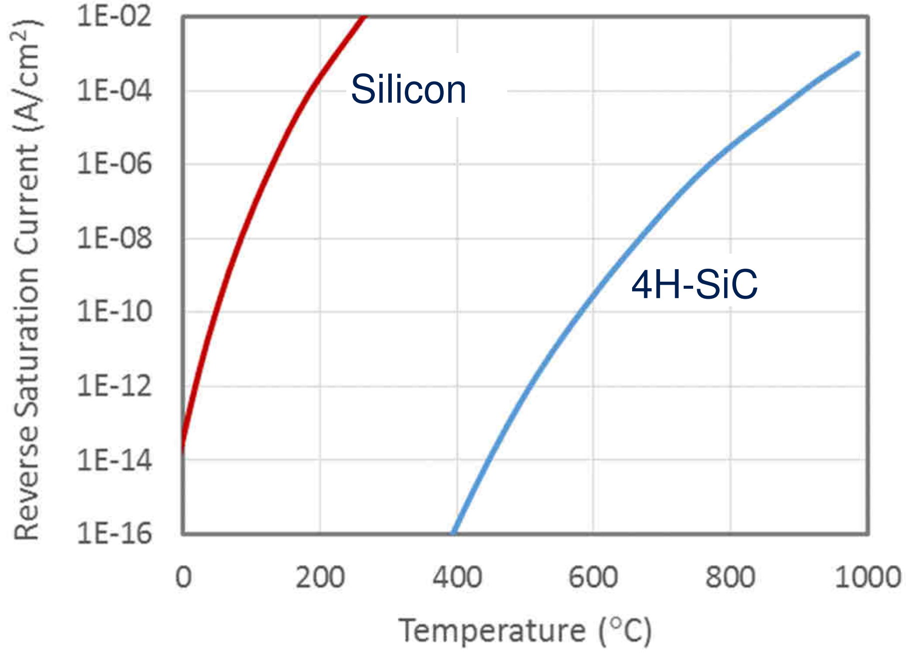
SiC provides low reverse leakage current up to high temperature

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

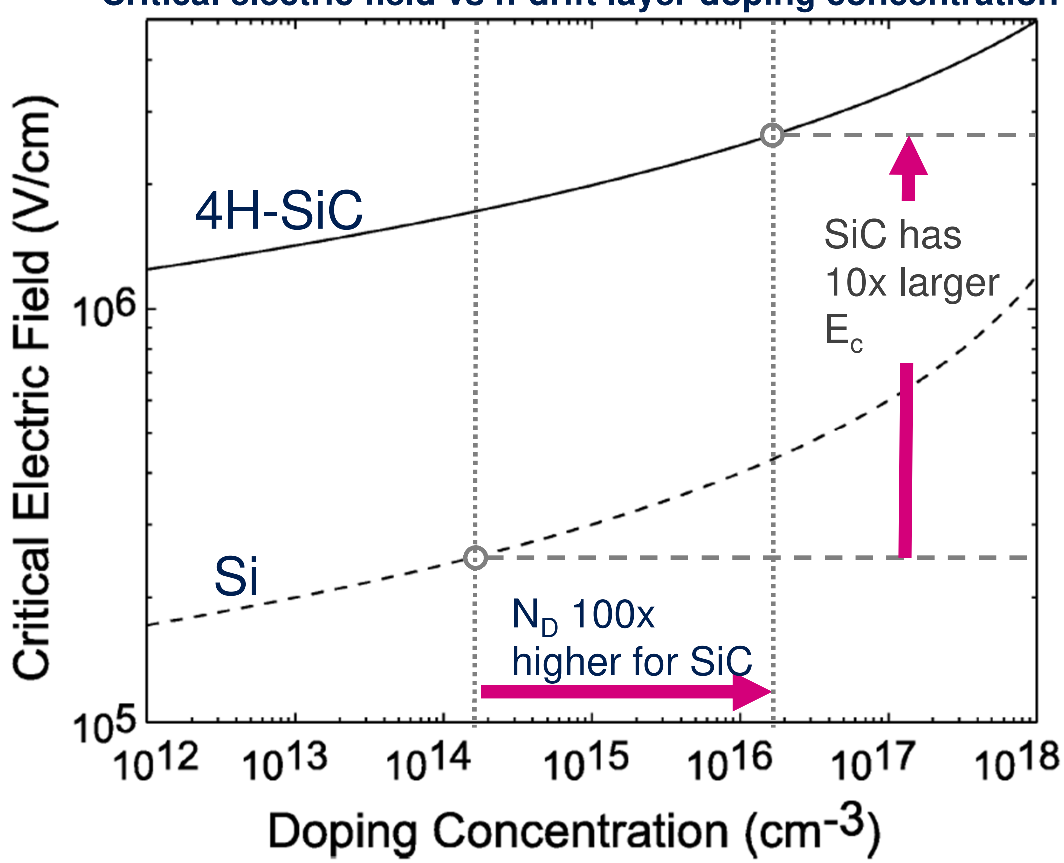


Critical electric field

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

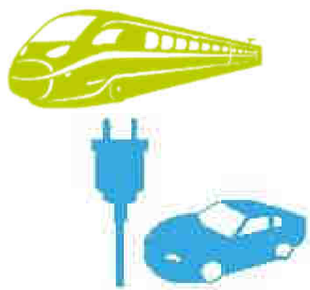
Material	Drift layer doping for BV=1200V
Si	1.5e14 cm^{-3}
SiC	1.6e16 cm^{-3}

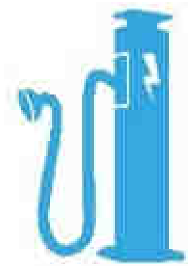
Critical electric field vs n-drift layer doping concentration



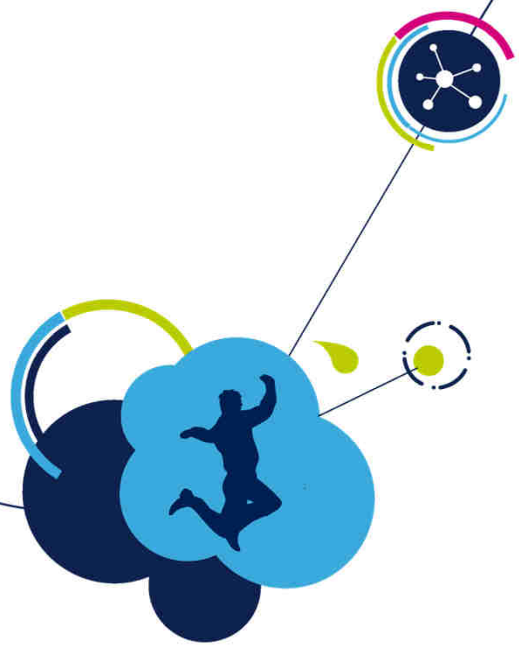
Note: circles show N_D required for 1200V NPT design

Key Applications for SiC





HEV/EV & Traction	SMPS & PFC	Solar Inverter	OBC & Charging station	Industrial Drives



SiC Power MOSFETs

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Benefits of SiC MOSFETs

Key Benefits

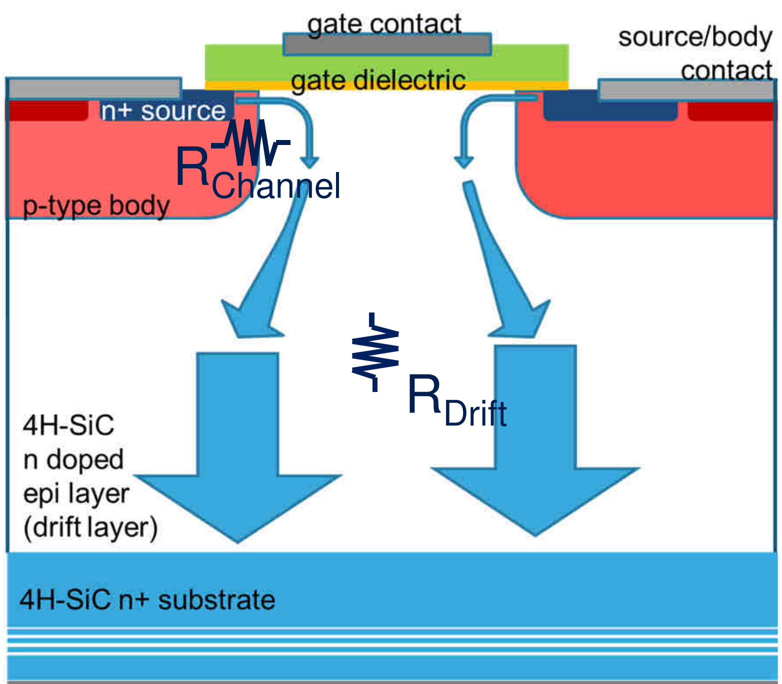
Extremely low Switching Losses and Ultra-Low $R_{DS(on)}$
Higher operating frequency for smaller and lighter systems

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

High-Voltage DMOSFET Structure



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

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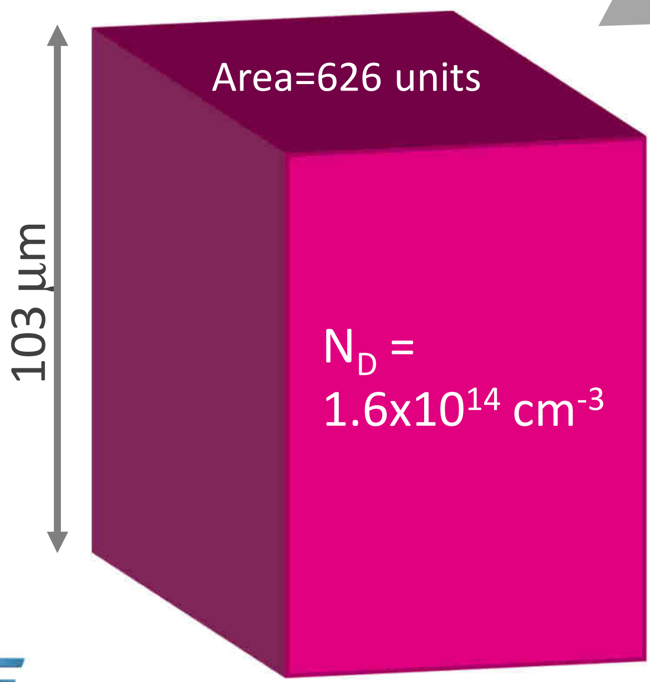
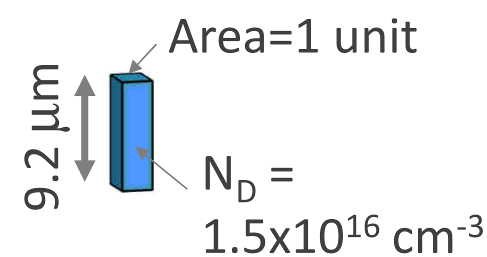
Drift layer dimensions for 1200V DMOSFET

SiC vs. Silicon

Silicon | **for columns of equal resistance** | **SiC**





For equal drift layer resistance at T_j=25C:

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

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

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

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

SiC offers dramatic reduction in device footprint!

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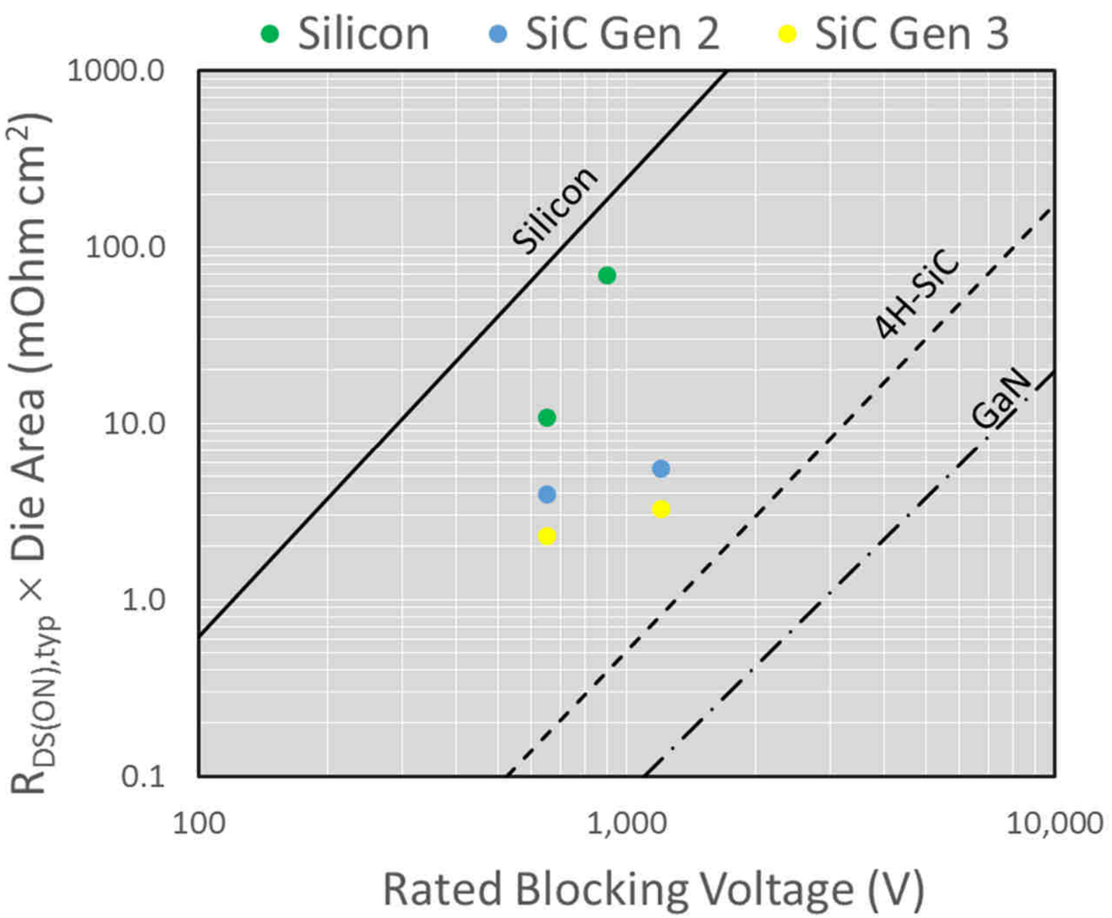
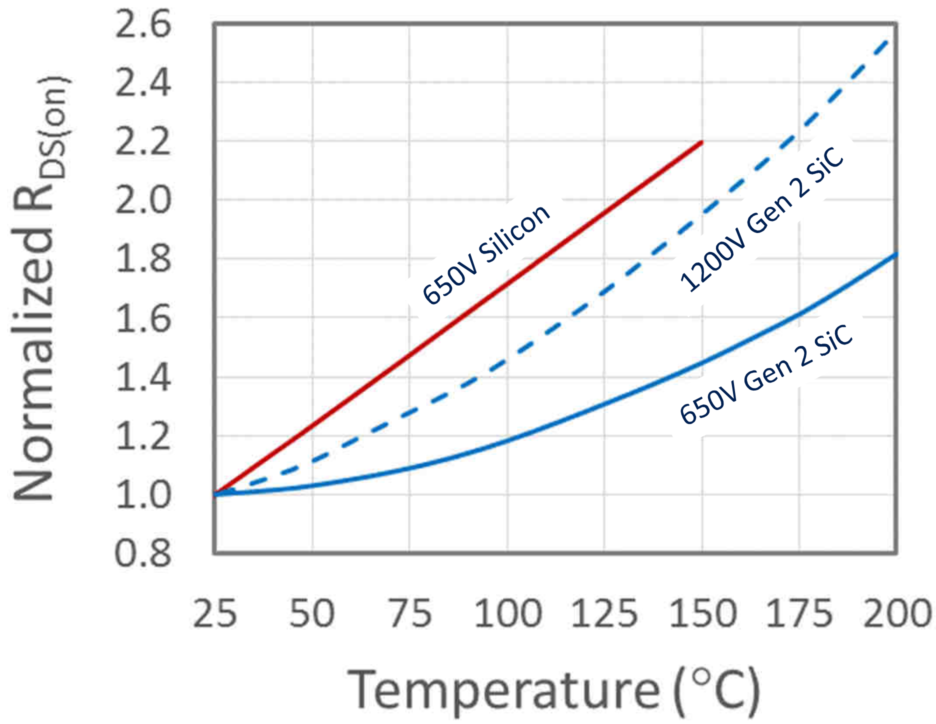
MOSFET $R_{DS(on)}$ Figure of Merit

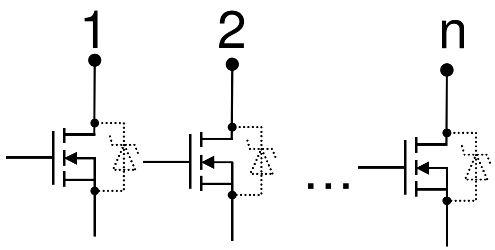


$R_{DS(on)}$ variation with temperature

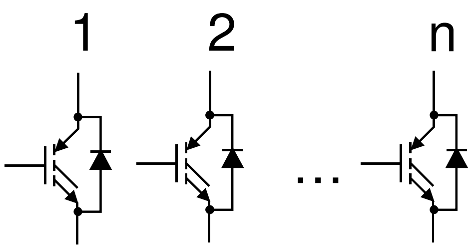


ST is the only supplier to guarantee max Tj as high as 200°C in plastic package

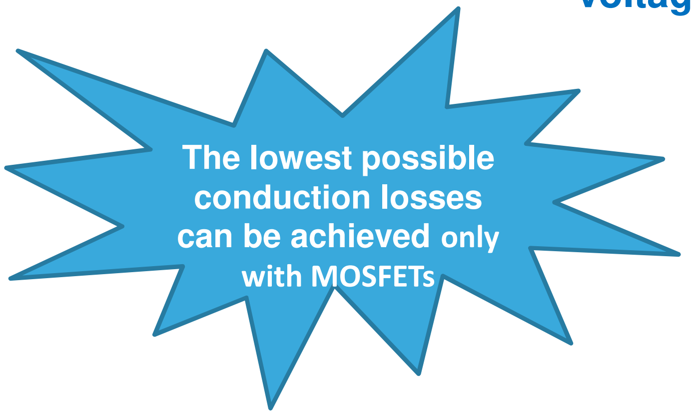
SiC MOSFET Allows Lowest Conduction Losses

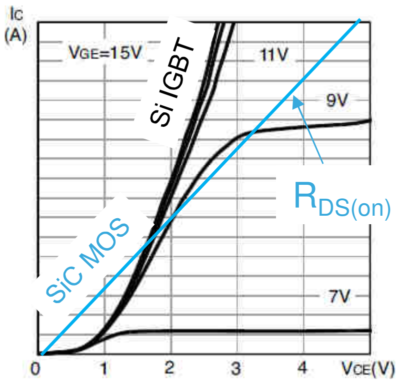


When "n" MOSFET are paralleled the total $R_{DS(on)}$ must be divided by "n" allowing ideally zero conduction losses



When "n" IGBTs are paralleled the $V_{ce(sat)}$ doesn't decrease linearly, the minimum achievable on-state voltage drop is about 0.8 – 1V





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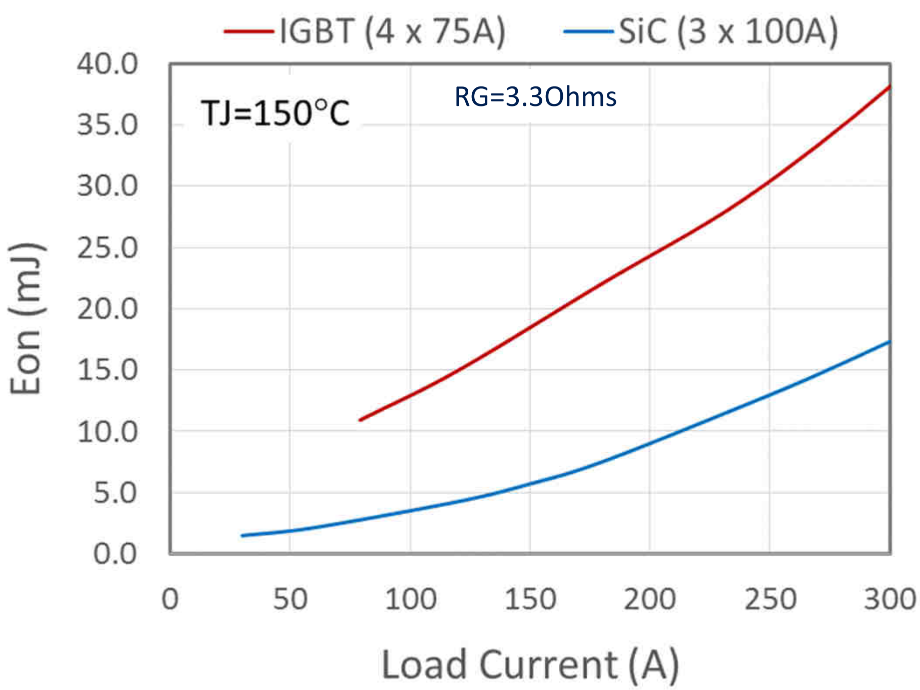
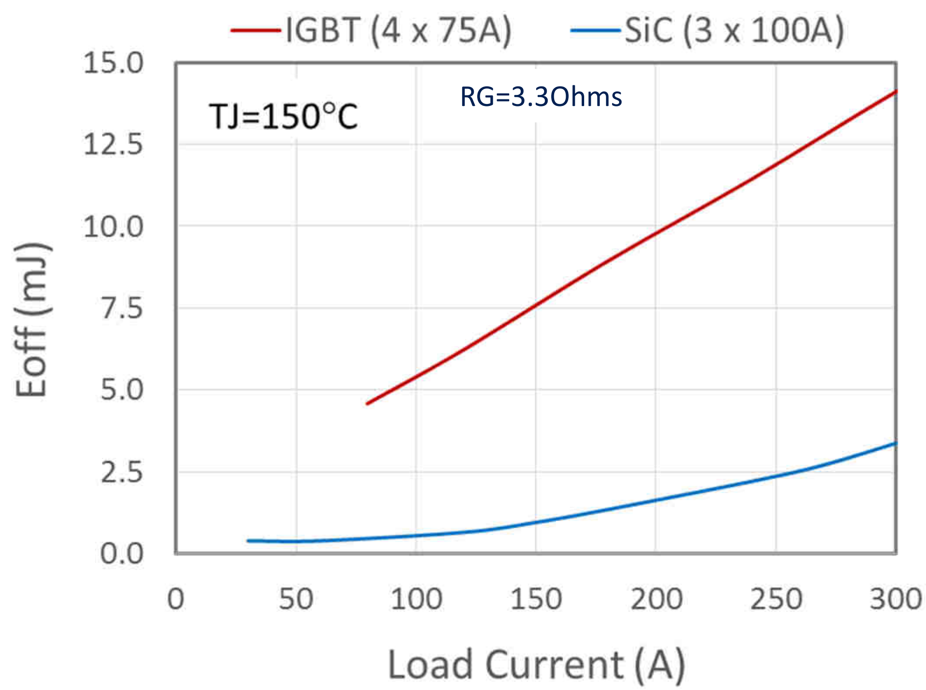
Switching energies for 1200V rated devices

IGBT vs SiC MOSFET





IGBT: 4 x FGY75T120SQDN-D (1200V, 75A, 46 mm^2 per die)
SiC MOSFET: 3 x SCT110N120G3D2AG (1200V, 100A, 26 mm^2 per die)

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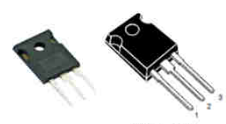
SiC MOSFETs in Production

V_{DS} [V]	$R_{DS}(on)$ @ 25 ºC [Ω]	Id	Package	P/N
1200	0.052	65	HiP247, H2PAK-7	SCT50N120 SCTWA50N120 SCTH50N120-7
	0.08	80	HiP247, H2PAK–2	SCT30N120 SCTWA30N120 SCT30N120H
	0.169	20	HiP247, H2PAK–2	SCT20N120 SCT20N120AG SCTWA20N120 SCT20N120H
	0.52	12	HiP247, H2PAK–2	SCT10N120 SCT10N120AG SCTWA10N120 SCT10N120H
650	0.045	45	HiP247, H2PAK–7	SCTH35N65G2V-7 SCTH35N65G2V-7AG SCTW35N65G2V
	0.018	90	HiP247, H2PAK–7	SCTW90N65G2V SCH90N65G2V-7
	0.020	100	HiP247	SCTE100N65G2AG



HiP-247 (STD & LL) ™

H2PAK
2 and 7 leads

- HiP-247 rated at 200°C Tj max
- H2PAK-7L (with kelvin source) SMD option (175°C Tj max)

Automotive Grade

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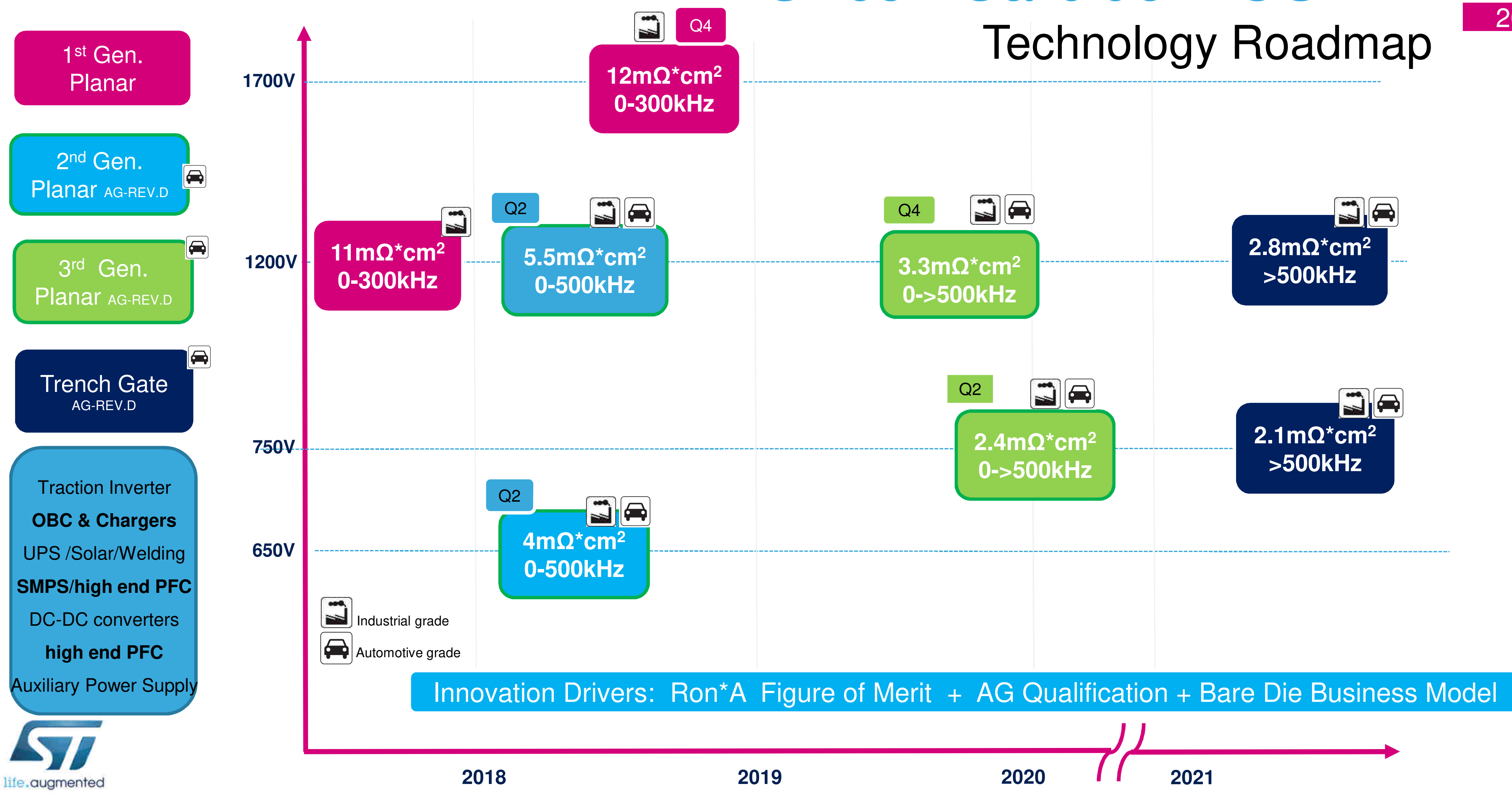
Silicon Carbide MOSFET
Technology Roadmap



SiC MOSFET driving requirements

- Driving a SiC MOSFET is almost as easy as driving a silicon MOSFET:
  - Just need V_{GS} = 20V to get the right $R_{DS(on)}$
  - Adequate current capability to ensure high speed (2-3 A would be the best)
- Very simple and very mature standard gate drivers can be used
  - ST TD350 + push-pull stage (to increase current capability) in production
  - The new ST isolated GAPdriver available now
- A detailed *Application Note* focused on “how to drive a SiC MOSFET” has been published on st.com: **AN4671**

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SiC MOSFET benefits

- Switching losses are dramatically reduced even in hard-switching topologies
- Unlike the IGBT, the MOSFET has no turn-on knee voltage giving low conduction losses across the entire load range
- The ONLY SiC alternative that offers intrinsic body diode with very low reverse recovery charge
- Easy to drive – use of conventional gate drivers ensures low component count
- Reliability – Very good final Result and qualified @ 200 °C!

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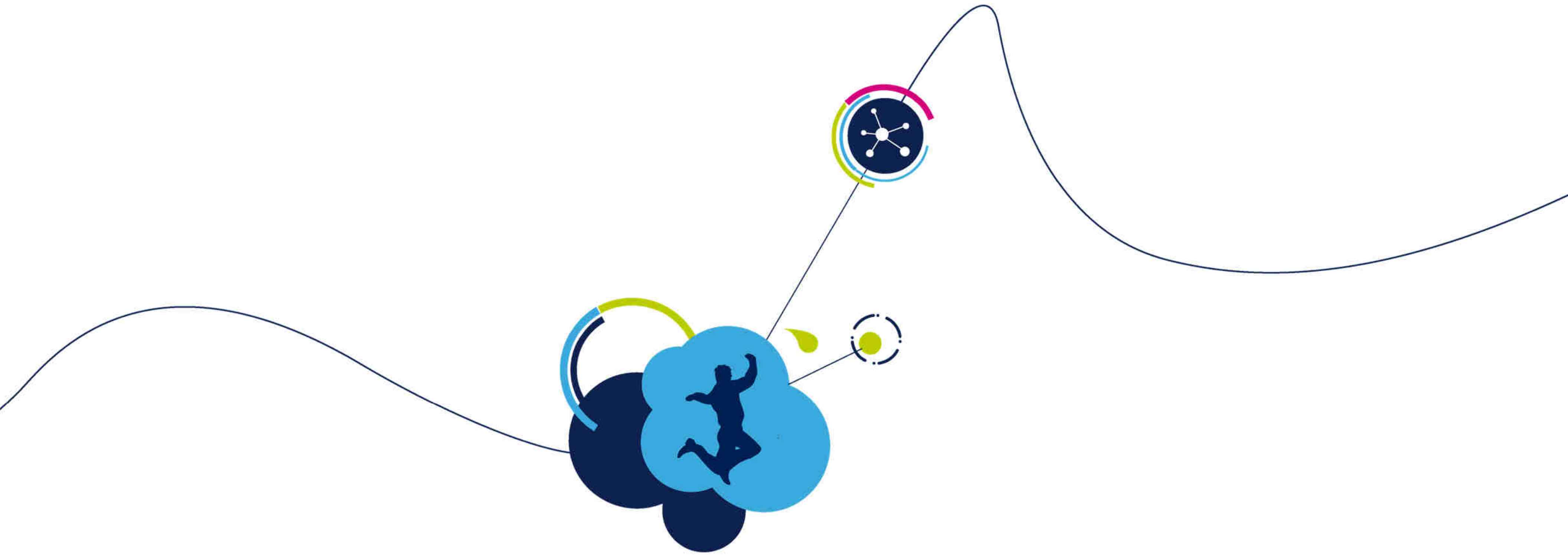

SiC Schottky Diodes

Enabling 1200V Diodes with High Efficiency

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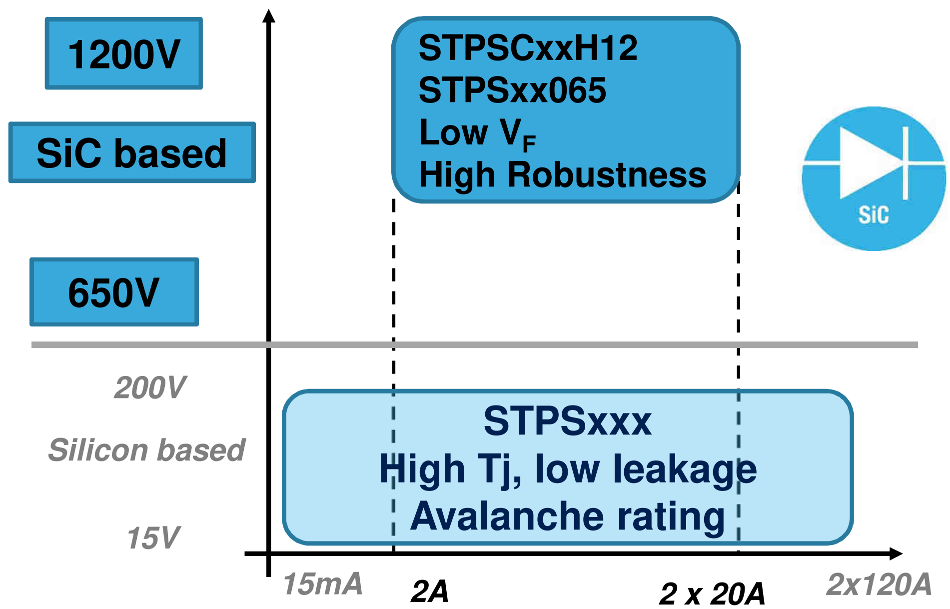
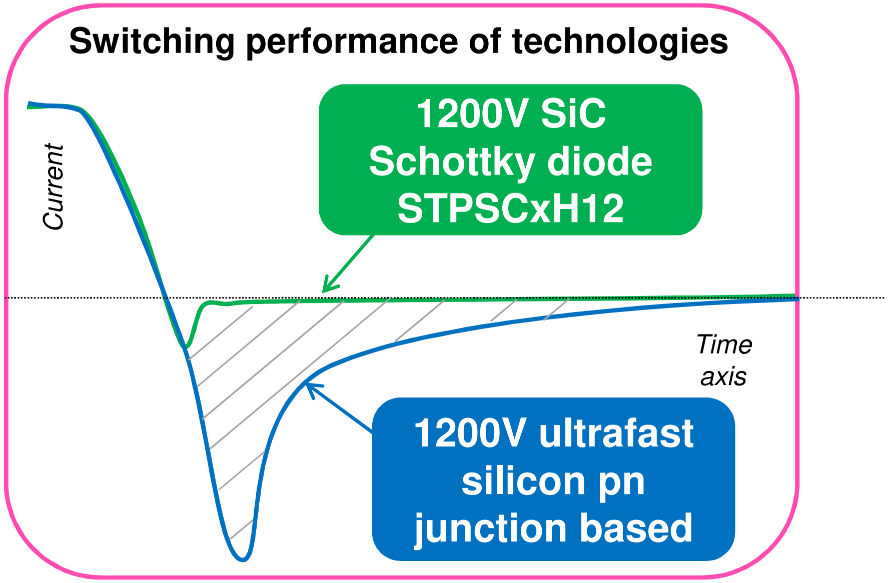
SiC allows Schottky diode structure to be used at much higher breakdown voltage vs Silicon versions



Improved switching performance is key advantage of SiC Schottky diodes



1200V SiC diodes provide higher system efficiency, remain cooler during operation

Key features of latest ST SiC Schottky diode technology

1200V SiC Schottky Diode Technology

- Negligible reverse recovery loss
- Based on new design to improve V_F/I_{FSM} trade-off
- Wide range of available sizes: 2A to 40A.
- Low VF (1200V SiC Schottky has best-in-class VF)
- High forward and reverse surge robustness
- Low leakage current for higher reliability
- AEC-Q101 versions available

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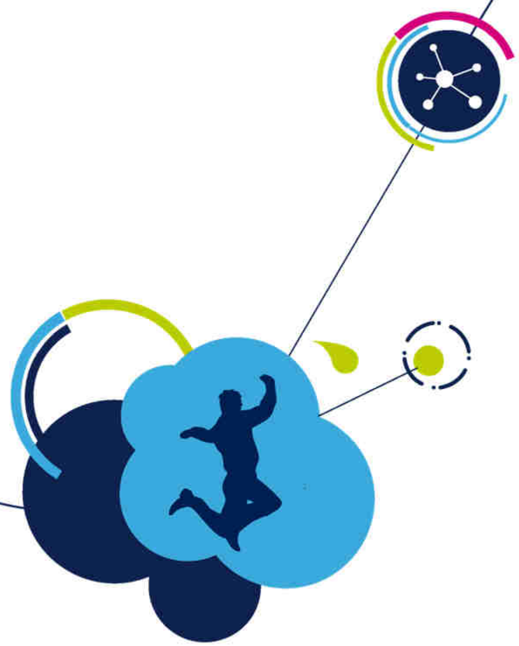
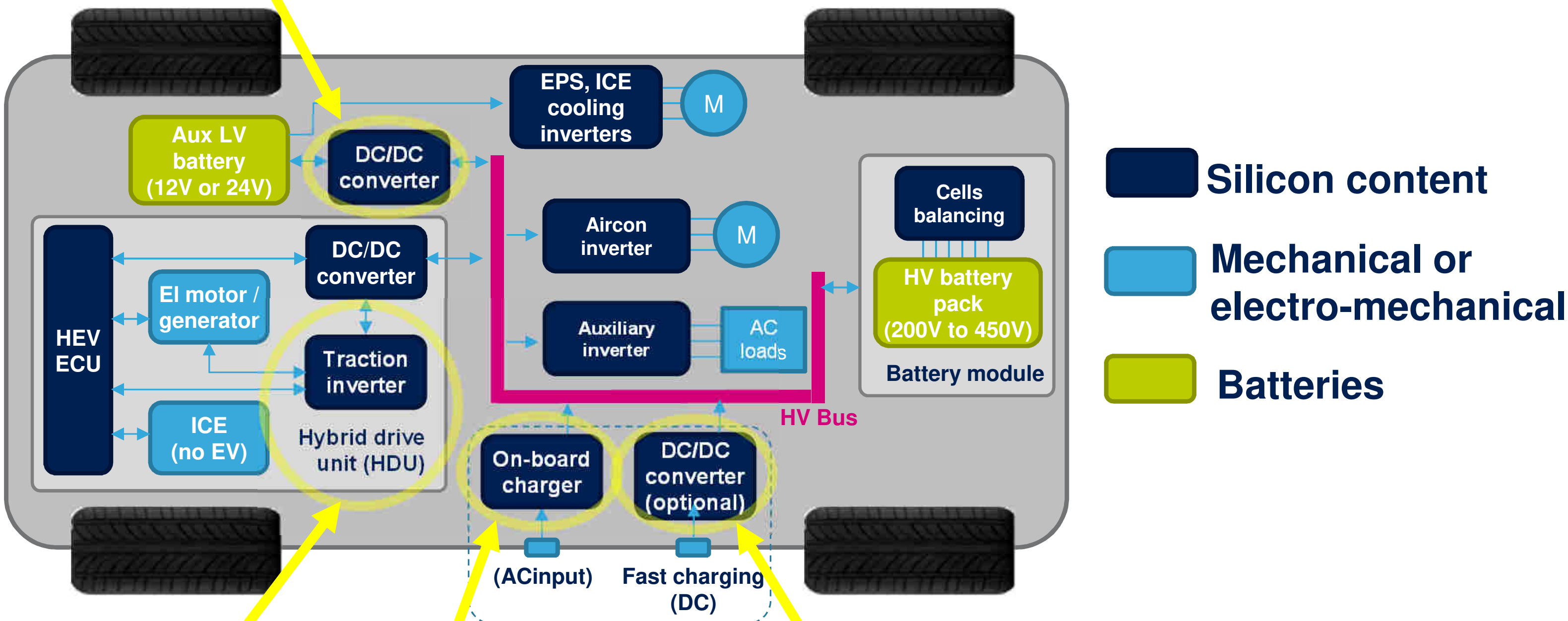


Overview of EV/HEV Power Electronics

e-Vehicle block diagram

HEV/EV

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



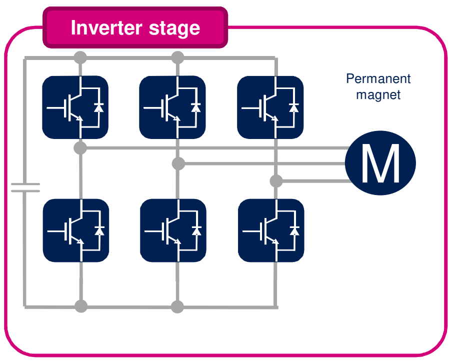
Output Power (EV): **80kW — 250kW**
IGBT → SiC MOSFET
12kHz and higher

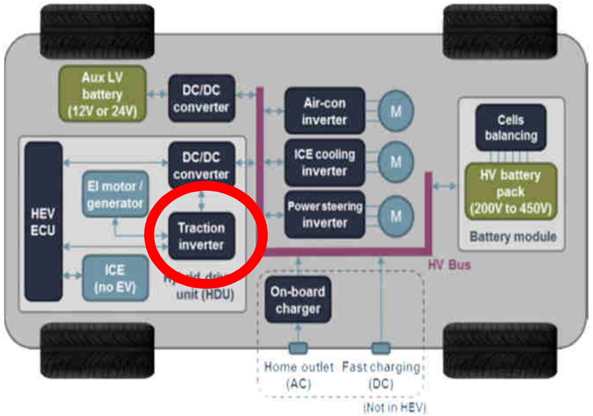
Output Power: **20kW**
SiC MOSFET/SiC SBD
50kHz – 200kHz

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

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 t0 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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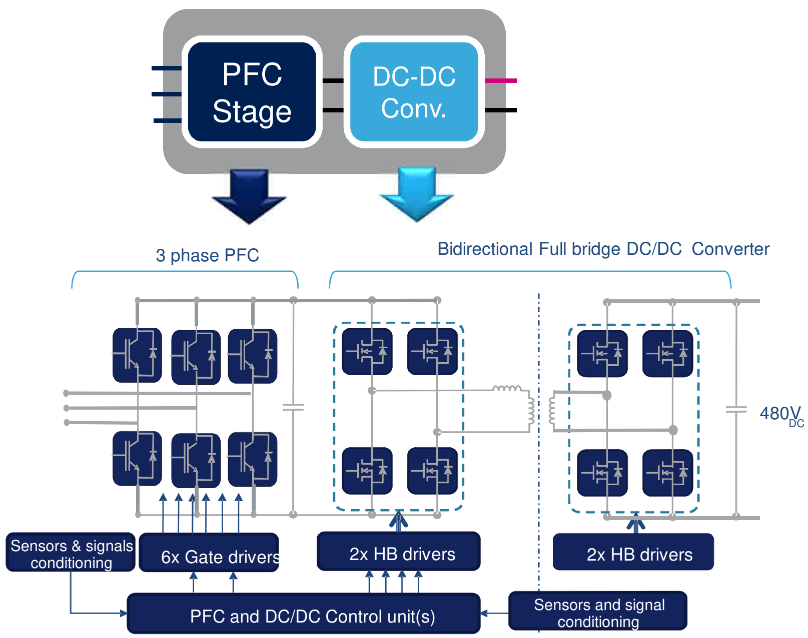
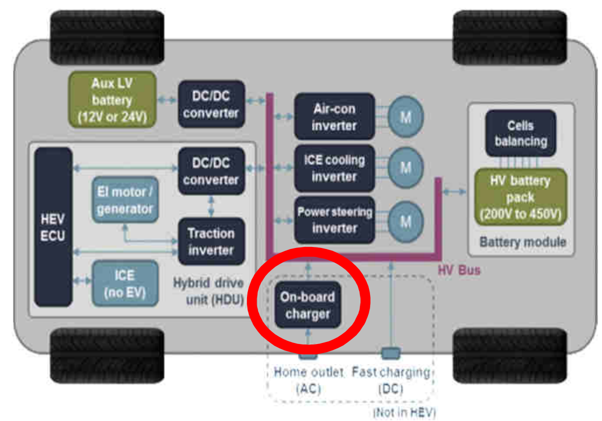
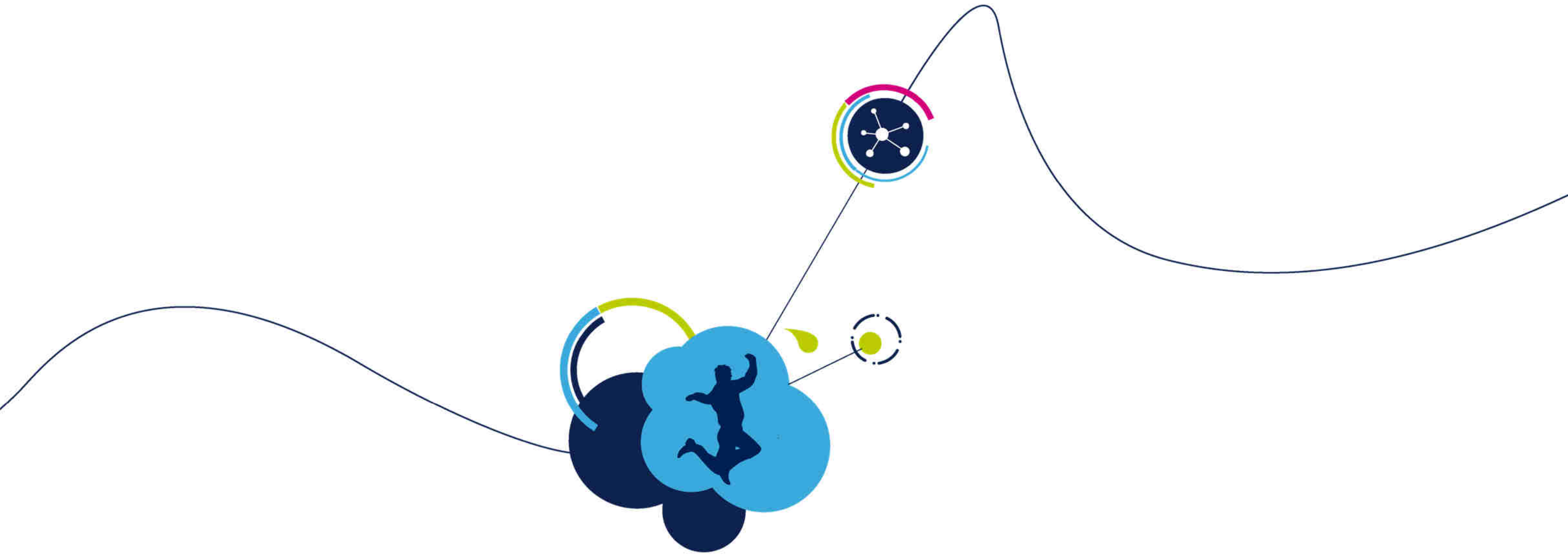
Battery charger for HEV/EV





Single-phase architecture→ SiC MOS 650V

Three-phase architecture→ mainly SiC MOS 1200V



80kW EV Traction Inverter Power Loss Estimation:

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

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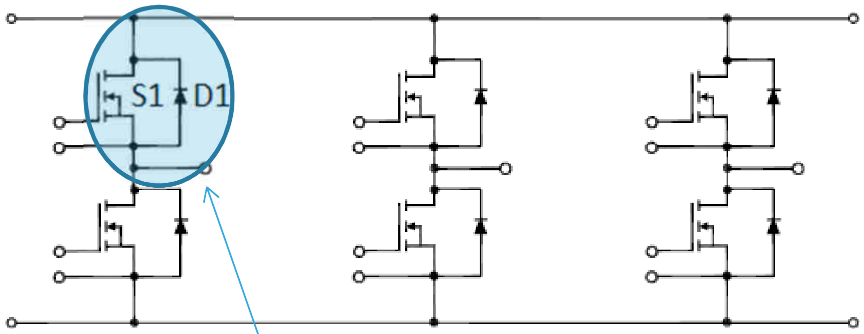
Operating conditions

- 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

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Power loss at peak condition
(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	Negligible
(S1+D1) Total losses* (W)	**662.2**	**399.2**
Junction Temperature (°C)	**134.2**	**151.5**

SiC vs Si per switch (S1+D1)

- 3.5x smaller area
- 3.4x lower
- 40% lower
- T_J ~ 80% T_{jmax}

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

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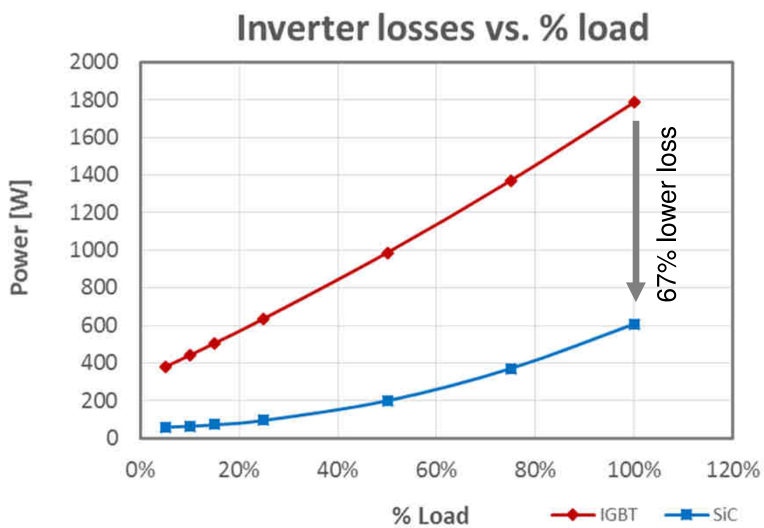
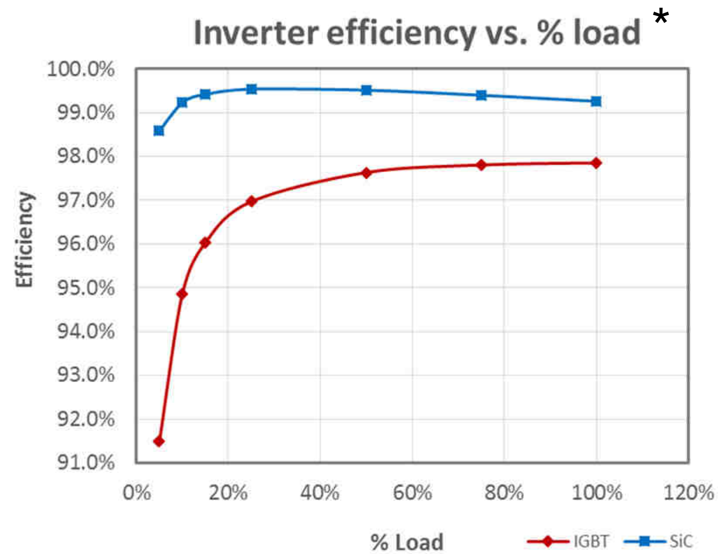
SiC Solution: lower losses, higher efficiency

f_{sw}=16kHz, 100% load =120A_{rms}





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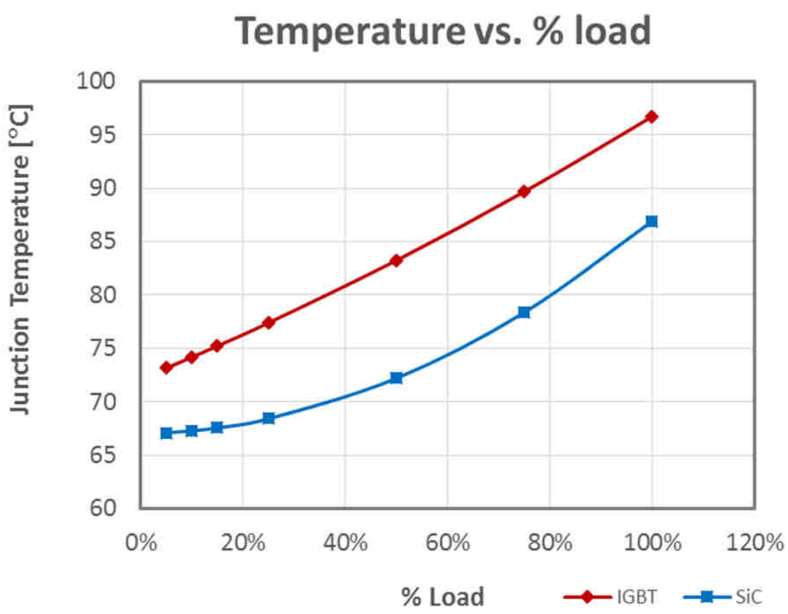
* The simulated efficiency takes into account only the losses due to the switches and diodes forming the bridge inverter

Remarks about junction temperature

f_{sw}=16kHz, 100% load =120A_{rms}



- $R_{thJ\text{-}C(IGBT\text{-}die)}$=0.19℃/W
- $R_{thJ\text{-}C(SiC\text{-}die)}$=0.30℃/W

- **SiC solution is better than Silicon in reliability since SiC has lower $\Delta(T_j\text{-}T_{fluid})$ up to 100% load.**
- **Cooling fluid temperature: 65℃ for both SiC MOS and Si IGBT, this means the IGBT cooling system must be more efficient due to IGBT higher losses**

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SiC MOSFET enables EV cost savings

Battery cost savings

EV traction inverter runs at ~ 15% load on average

At 15% load, SiC based inverter gives 3.4% efficiency improvement

Battery capacity required for SiC based EV is only 96.6% that of IGBT based → **SiC based EV needs only 82.1 kWh battery to give same range as IGBT based version with 85 kWh battery**

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

Can specify inverter heat sink assuming dissipation at 125% rated load (for added margin):

Switch Type	IGBT	SiC MOSFET
Inverter Power Dissipation	2235W	910W

SiC based inverter will only need to dissipate **41% as much heat** versus 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 67% lower loss:
  - Much lower loss at low load allows smaller battery for same range
- 60% 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

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STGAP1AS: advanced galvanically isolated gate driver

AEC-Q100 grade 1

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

5 A sink/source current

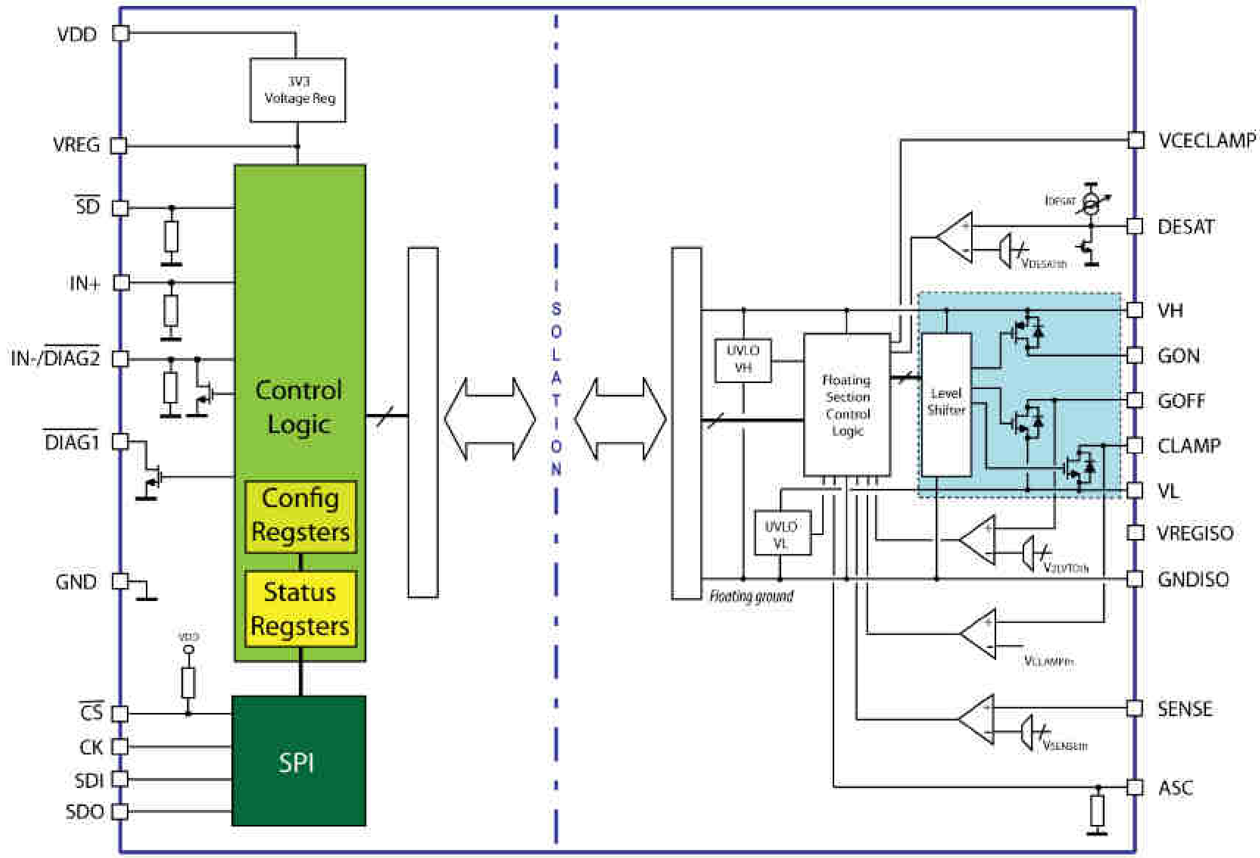
High Voltage Rail up to 1.5 kV
Wide drive voltage range (+ 36 V / -10V)

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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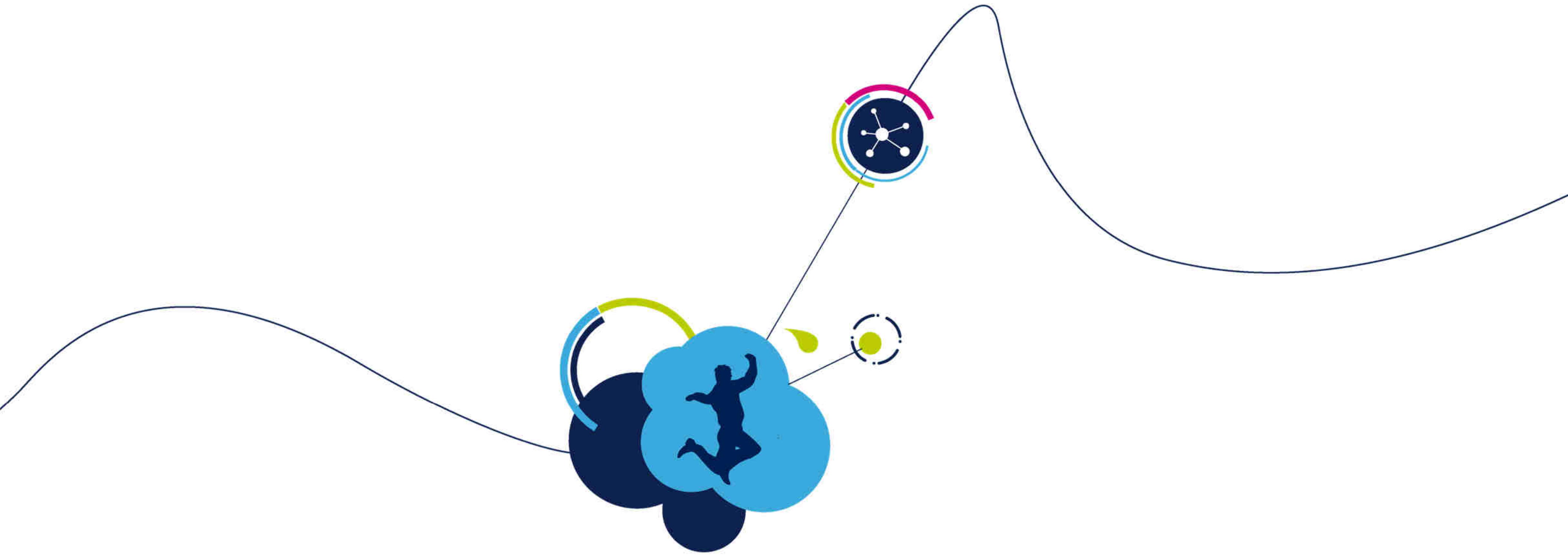

Conclusions

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Component cost considerations

SiC MOSFET vs IGBT (1200V)

- Today
  - Price of SiC MOSFET is 4 – 4.5x relative to IGBT
- Near Term (2 – 3 years)
  - 2.5x vs IGBT, cost reduction from improvements in $R_{DS(on)}$ x area FOM, and higher volume
- Long Term (5 – 10 years)
  - Further development and larger wafer diameter needed to continue to bring cost down

SiC MOSFET price roadmap

- Today SiC represents an attractive but still expensive solution for many applications
  - Valid when considering just the component cost
- For cost benefit of SiC to be recognized, must consider cost impact on whole system as SiC enables:
  - Smaller cooling system (saving space and weight)
  - Smaller footprint (more compact electronics)
  - Higher efficiency (less energy used)
  - Ability to use higher switching frequency (smaller passive components)
  - Higher reliability (smaller ΔT across load range)

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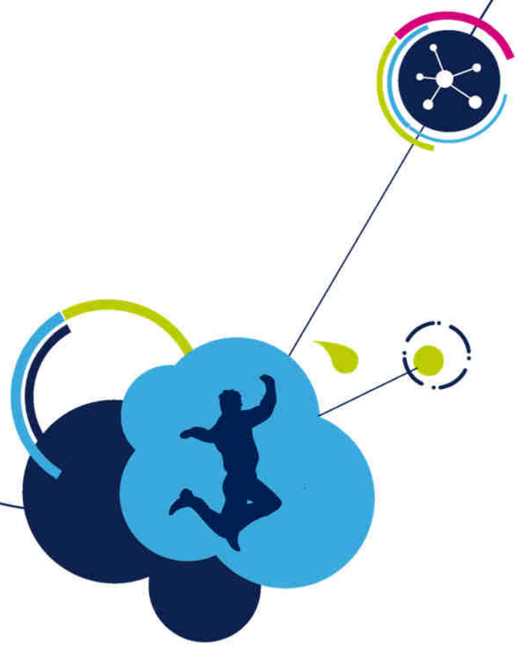
Conclusion

- 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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