How SiC Can Boost Efficiency and Reduce Costs in Power Conversion

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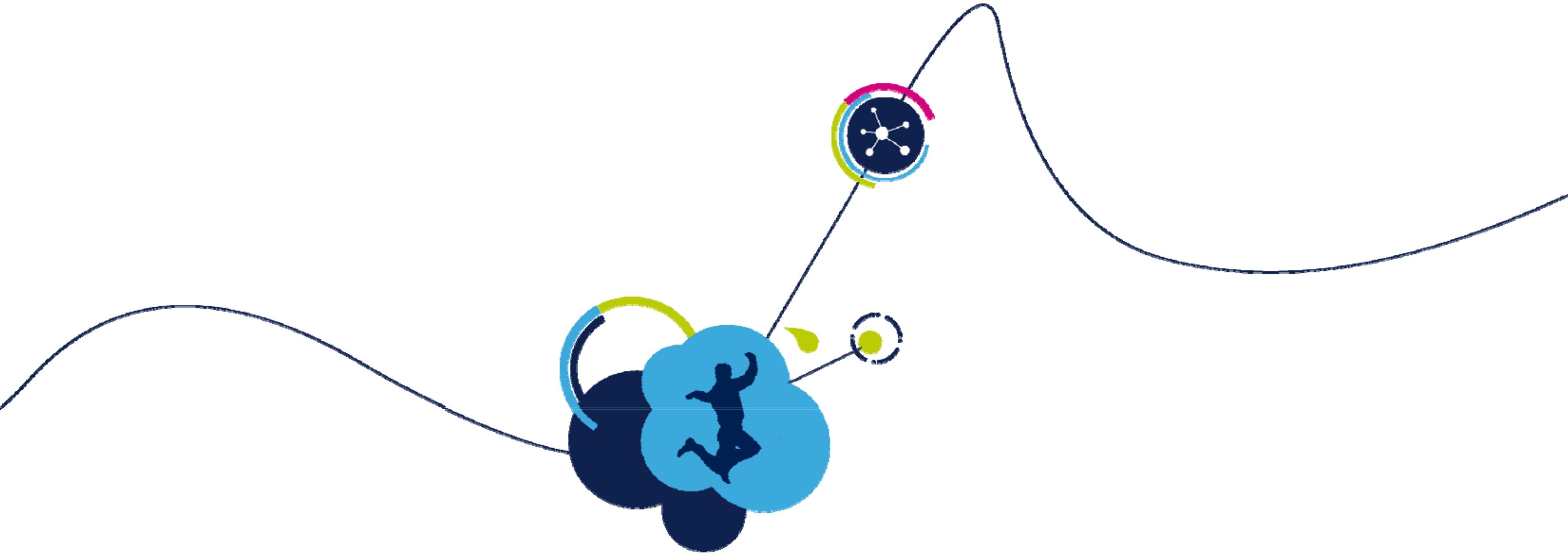
Agenda

Time	Presentation	Speaker
3:50	SiC MOSFETs	Jeff Fedison
	Overview of EV/HEV Power Electronics	
	EV Traction Inverter Design Example	
4:30	Conclusion	



SiC MOSFET

A Real Revolution for High-Voltage Power Switches

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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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Benefits of SiC MOSFETs

Key Benefits

Extremely low Switching Losses and
Ultra-Low $R_{DS(on)}$ especially at very high T_j

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

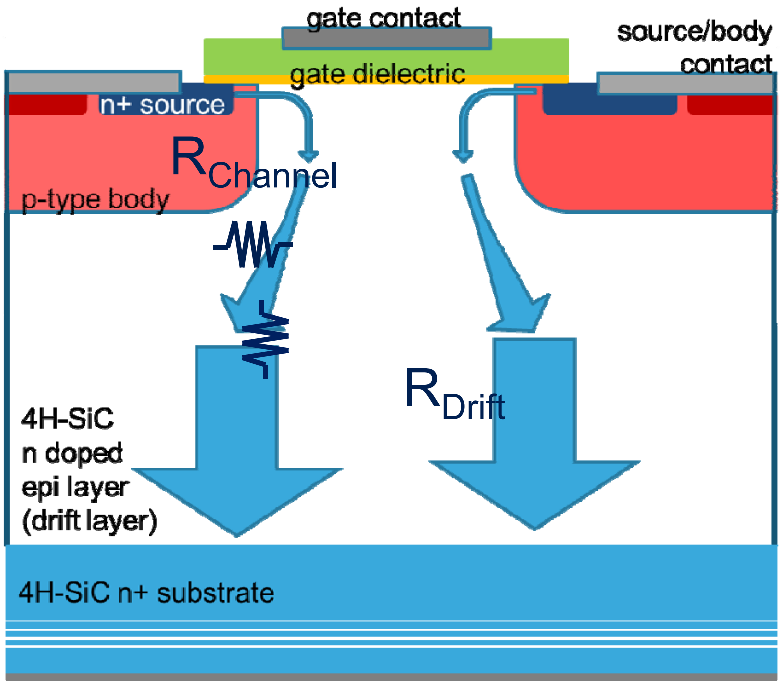
Easy to Drive

Fully compatible with standard Gate Drivers

Very fast and robust intrinsic body diode

More compact Inverter

High-Voltage DMOSFET Structure



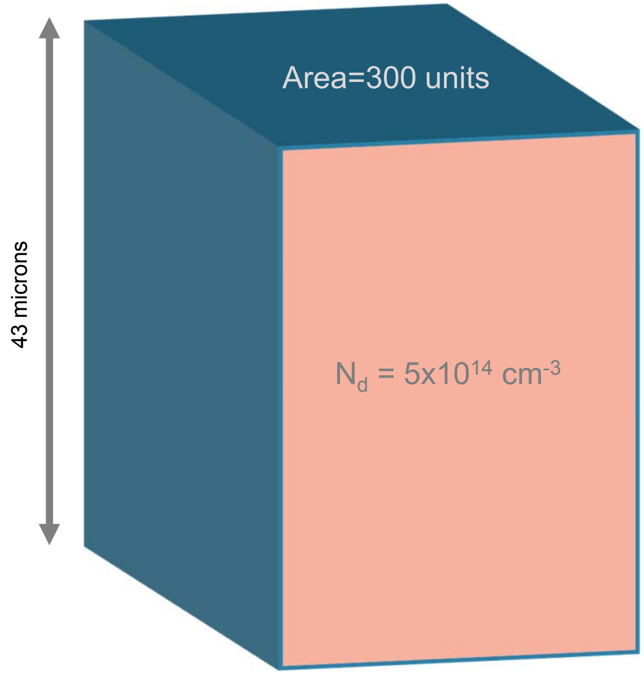
$R_{DS(on)}$ is determined mainly by R_{Drift} and to some extent $R_{Channel}$.

$R_{DS(on)}$ Entitlement for 650V DMOSFET

Silicon vs SiC

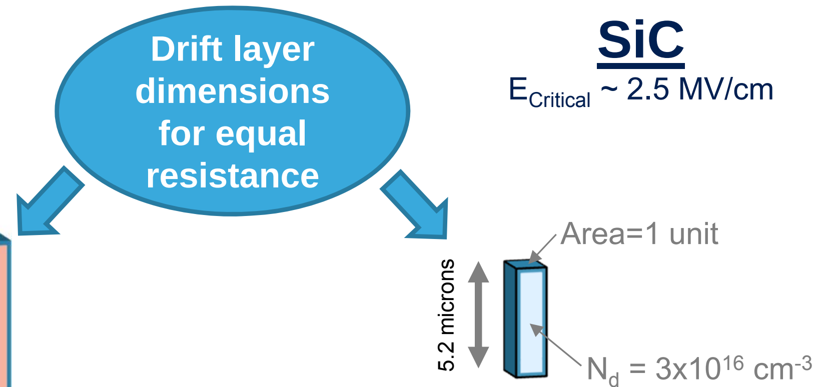
Silicon

$E_{Critical}$ ~ 0.3 MV/cm



SiC

$E_{Critical}$ ~ 2.5 MV/cm



For equal drift layer resistance at Tj=25C:

$$\text{AREA:}\quad \text{SiC} = \frac{1}{300}\,\text{Silicon}$$

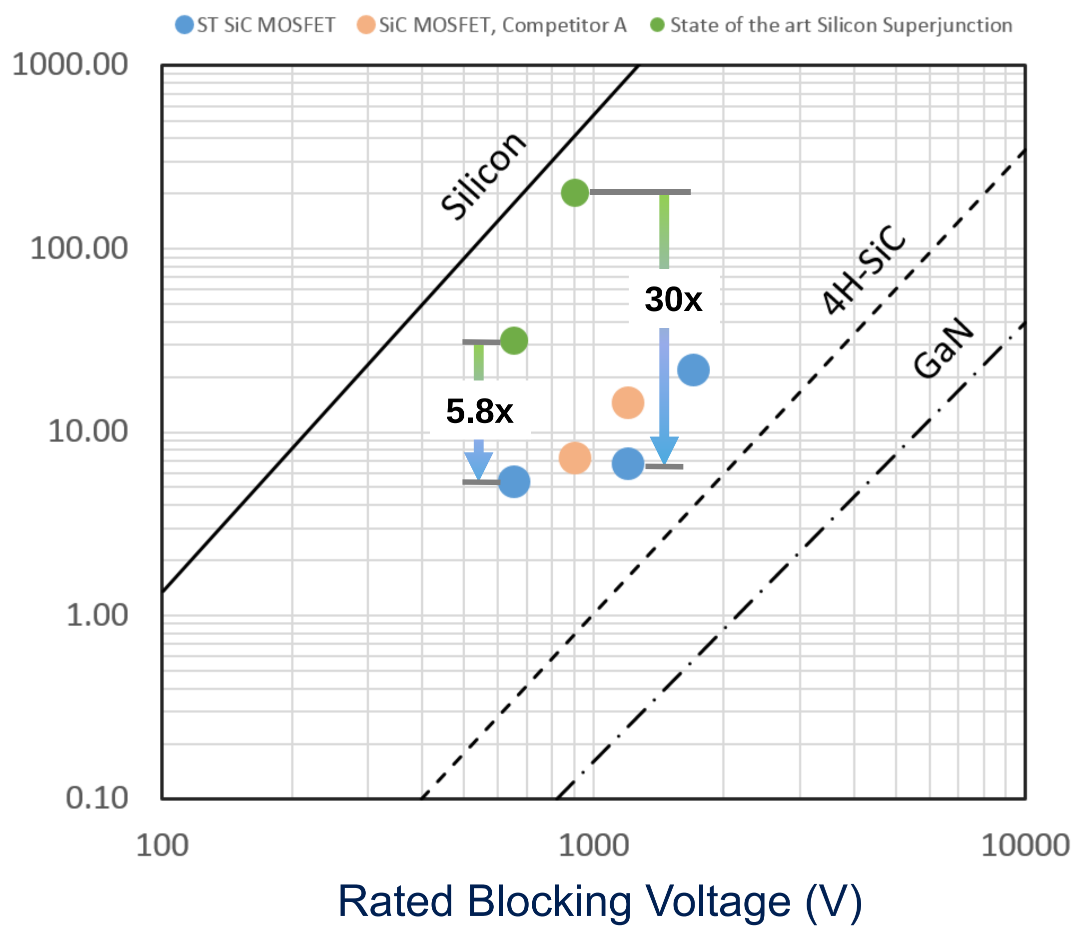
$$\text{THICKNESS:}\quad \text{SiC} = \frac{1}{8}\,\text{Silicon}$$

$$\text{CAPACITANCE:}\quad \text{SiC} = \frac{1}{44}\,\text{Silicon}$$

$$\text{THERMAL RESISTANCE:}\quad \text{SiC} = 12\ \text{Silicon}$$

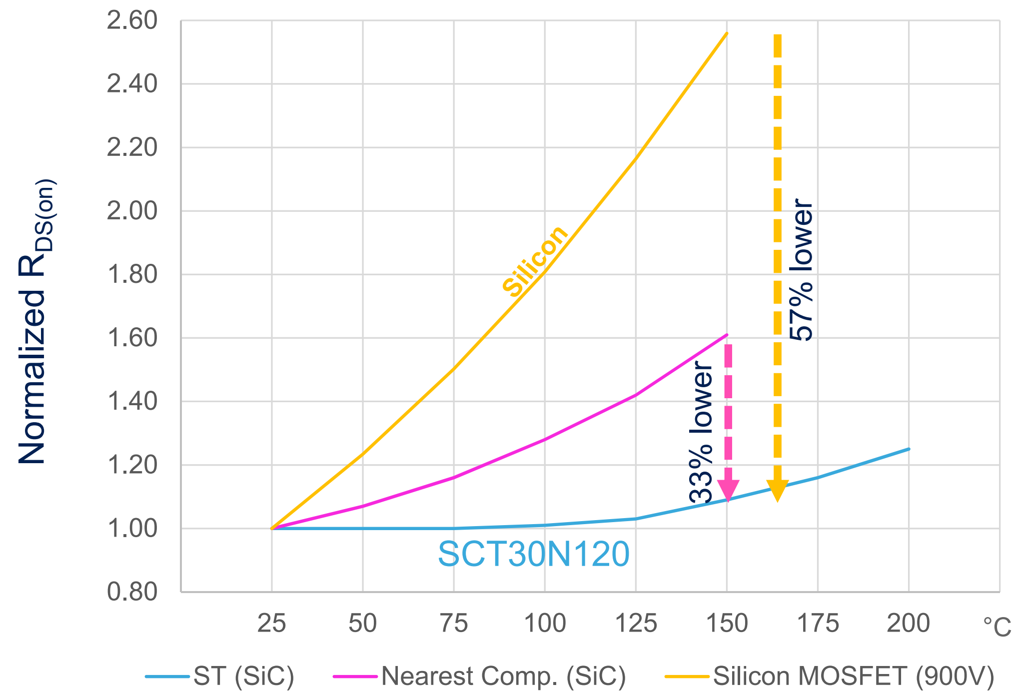
SiC offers dramatic reduction in device footprint.

MOSFET $R_{DS(on)}$ Figure of Merit at T_J=150C



$R_{DS(on)}$ Variation with Temperature

1200V SiC MOSFET

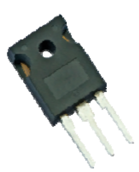


ST is the only supplier to guarantee max Tj as high as 200°C in plastic package

SiC MOSFETs in Full Production

1200V Series

V_{DS} [V]	$R_{DS}(on)$ typical @ 25°C [mΩ]	Id	Qg (nC)	Package	P/N
1200	52	65	*122*	HiP247 & Bare Die	SCT50N120
	80	45	*105*	HiP247 & Bare Die	SCT30N120
	169	20	*45*	HiP247	SCT20N120
	520	12	*21*	HiP247	SCT10N120



HiP-247™

Full Production in Q3

H2PAK
2 and 7 leads

Key Applications

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

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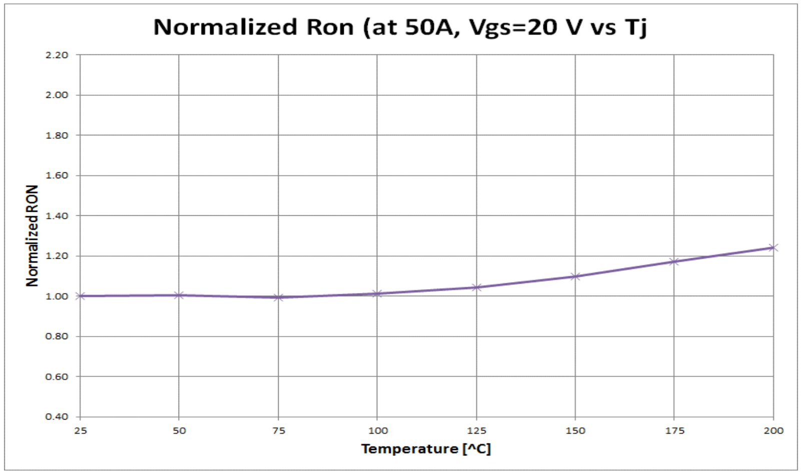
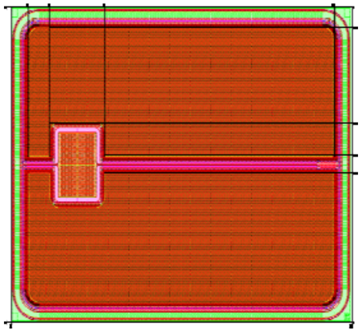
Gate Driving Voltage = 20 V
HiP247™ Package: T_{jmax}=200 °C

ST 650V 2nd Gen SiC MOSFET



SCTW100N65G2AG

- $R_{DS(on)}$ (typ @25°C) : 20 mOhm
- $R_{DS(on)}$ (typ @200°C) : 23 mOhm
- Q_g (typ) : 215 nC
- Package : HiP247™



- **ST SiC MOSFET shows lowest R_{on} increase at high temperatures**
- **ST is the only supplier to guarantee max T_j as high as 200°C**
- **Gate driving voltage = 20V**

Full Maturity: Q1 2018 (Industrial Grade)
Full Maturity: Q2 2018 (Automotive Grade)

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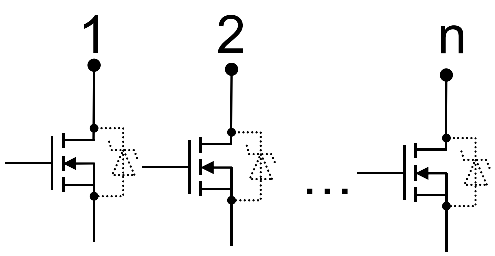
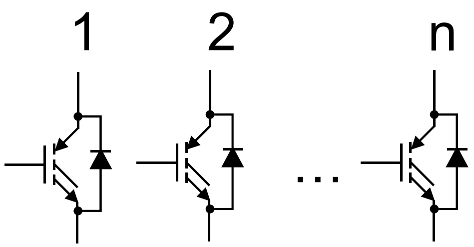
SiC MOSFET Allows Lowest Conduction Losses

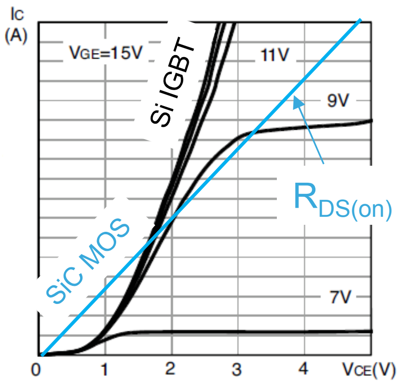


When "n" MOSFET are paralleled the total $R_{DS(on)}$ must be divided by "n" allowing ideally zero conduction losses



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

The lowest possible conduction losses can be achieved only with MOSFETs



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Hard-Switched Power Losses

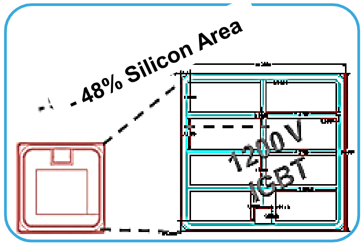
SiC MOSFET vs. Si IGBT

SiC MOSFET vs. trench gate field-stop IGBT						
Parameters & Conditions	Die size (Normalized)	V_{on} typ. (V) @ 25°C, 20A	V_{on} typ. (V) @ 150°C, 20A	E_{on} (µJ) @ 20A, 800V 25°C / 150°C	E_{off} (µJ) @ 20A, 800V 25°C / 150°C	E_{off} 25°C / 150°C difference (%)
SiC MOSFET	0.52	1.6	1.8	500 / 450*	**350 / 400**	+15% from 25°C to 150°C
IGBT	1.00	1.95	2.2	800 / 1300**	**800/ 1900**	+140% from 25°C to 150°C

* Including SiC intrinsic body diode Q_{rr} ** Including the Si IGBT copack diode Q_{rr}

SiC MOSFET

- Data measured on SiC MOSFET engineering samples;
- SiC MOSFET device : SCT30N120, 1200V, 34A (@100°C), 80mΩ, N-channel
- Si IGBT device: 25A(@100°C) 1200V ST trench gate field-stop IGBT ($T_{j\text{-}max}$=175°C)
- SiC switching power losses are considerably lower than the IGBT ones
- At high temperature, the gap between SiC and IGBT is insurmountable



SiC die size compared to IGBT

➢ SiC MOSFET is the optimal fit for High Power, High Frequency and High Temperature applications

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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 – System cost reduction
- 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
- Minimal increase in $R_{DS(on)}$ with temperature allowing higher temperature operation with good efficiency
- Easy to drive – use of conventional gate drivers ensures low component count
- Reliability – Very good final Result (qualified @ 200 °C!)

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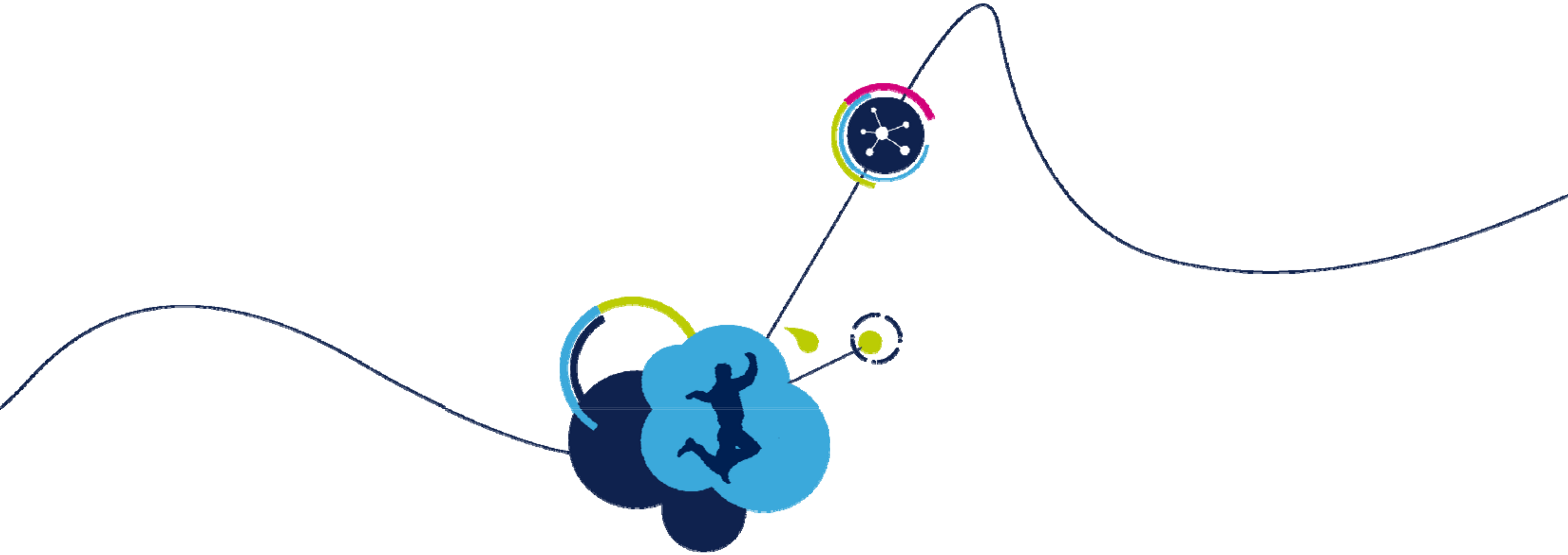

Overview of EV/HEV Power Electronics

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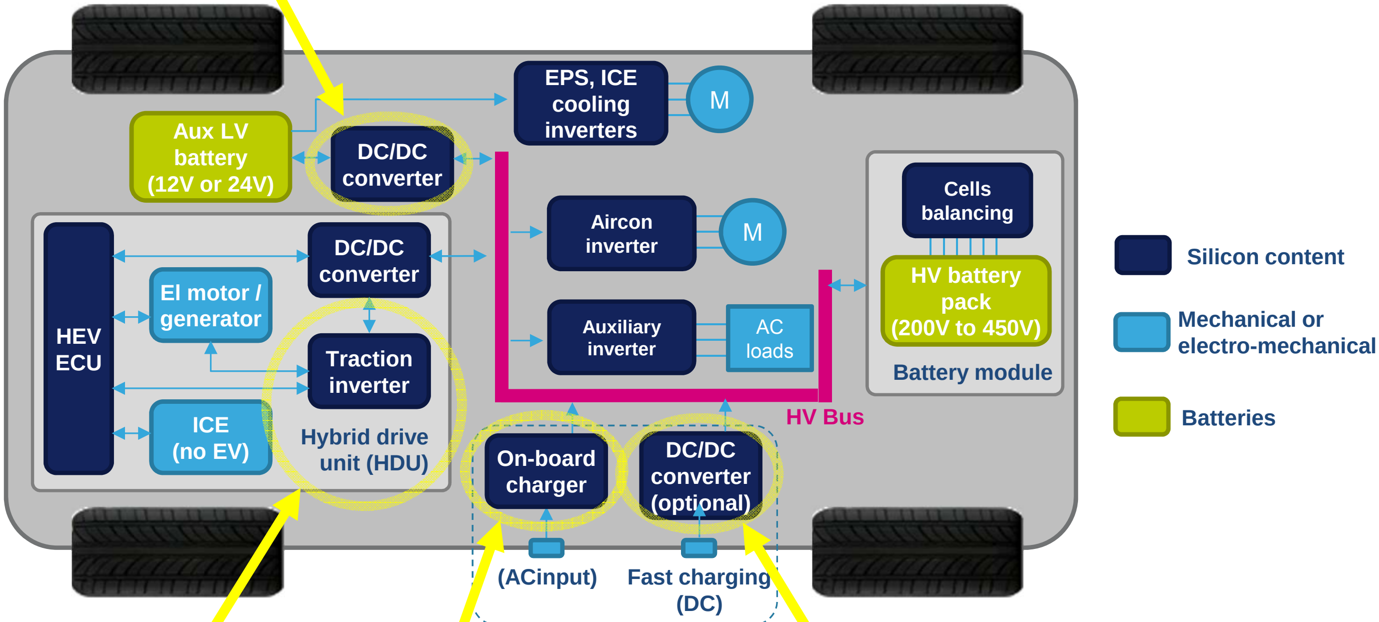
e-Vehicle Block Diagram

HEV/EV

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



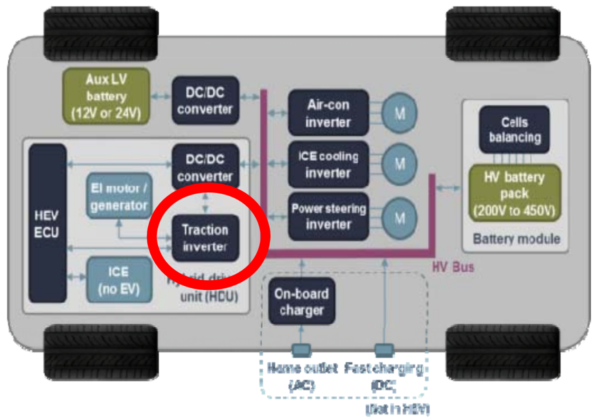
Output Power: **200kW**
IGBT → SiC MOSFET
Up to 20kHz

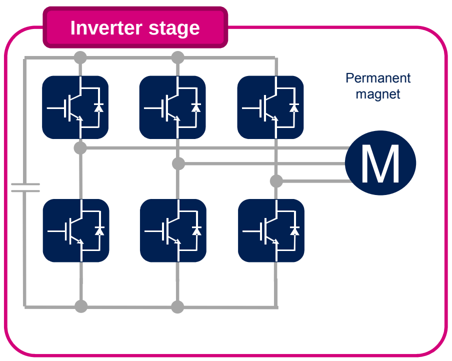
Output Power: **50kW**
Si MOSFET → SiC MOSFET
50kHz – 200kHz

Output Power: **20kW**
SiC Diode or SiC MOSFET depending on topology
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 on HV Bus when breaking the vehicle
- **Nominal power ranging from 10kW (ICE assistance) to 100kW (pure EV)**

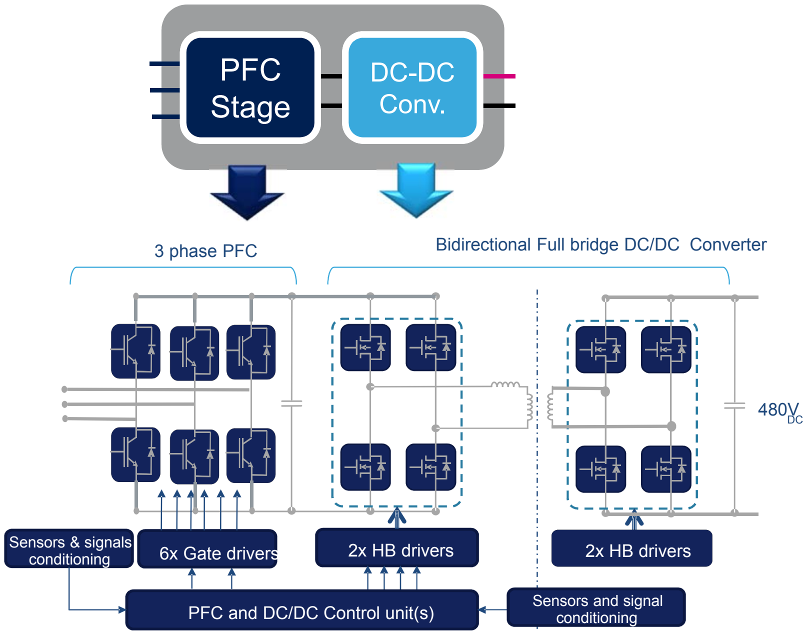


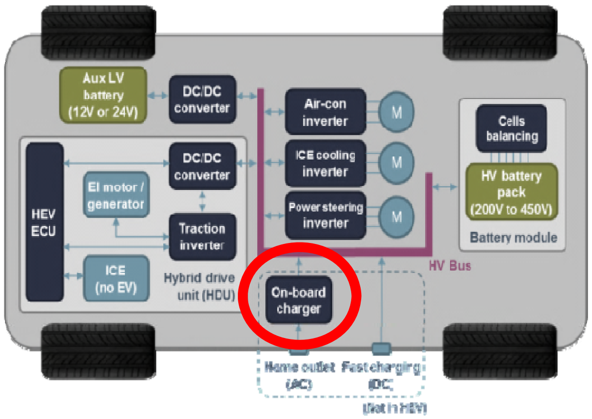


For bus up to 400V → SiC MOS 650V

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

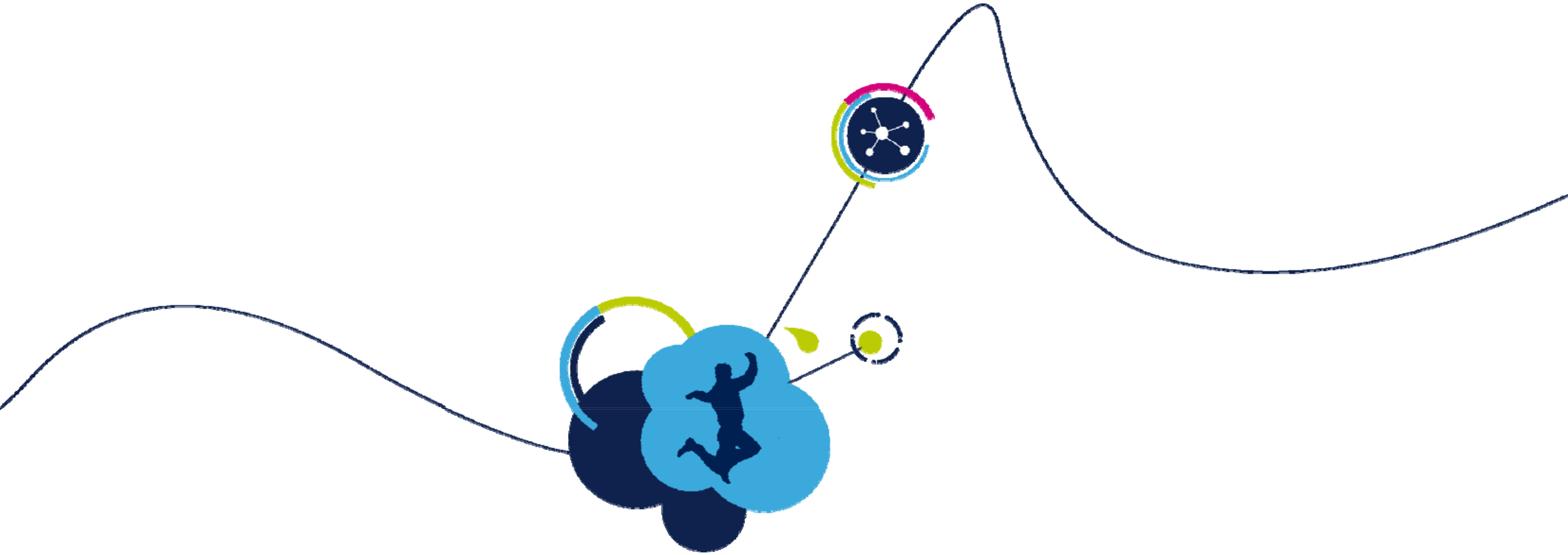
Battery Charger for HEV/EV





Single-phase architecture→ SiC MOS 650V

Three-phase architecture→ mainly SiC MOS 1200V

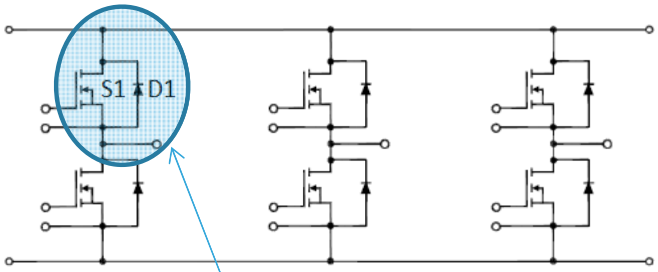


80kW EV Traction Inverter Power Loss Estimation:

650V SiC MOSFETs vs Existing Silicon IGBT-based Power Module

Operating Conditions

- Topology: Three phase inverter
- PWM Strategy: Bipolar
- Synchronous rectification (SiC version)
- DC-link voltage: 400V_{dc}
- Current 480Arms (peak) 230Arms (nom)
- Switching frequency: 16kHz
- V_{gs}=+20V/-5V for SiC, V_{ge}=±15V for IGBT
- Cos(phi): 0.8
- Modulation index (MI): 1
- Cooling fluid temperature: 85℃
- $R_{thJ-C(IGBT-die)}$=0.4℃/W; $R_{thJ-C(SiC-die)}$=1.25℃/W
- $T_j \leq 80\%*T_{jmax}$℃ at any condition



Si IGBT requires antiparallel Si diode, SiC MOSFET does not

Switch (S1+D1) implementation

4 x 650V,200A IGBTs + 4 x 650V,200A Si diodes
vs.
7 x 650V, 100A SiC MOSFETs SCTx100N65G2

Design Considerations

The devices were dimensioned in order to get a junction temperature equivalent to roughly 80% of the absolute maximum rating given in the datasheet at the peak power condition. The overall working conditions are:

- Peak-power condition $480A_{rms}$, 10sec.
- Normal working condition up to $230A_{rms}$.

Power Loss at Peak Condition
(480A_{rms},10sec)

* Typical power loss values

Loss Energy	Si-IGBTs + Si-diodes Solution	Full-SiC Solution	SiC vs Si per switch (S1+D1)
Total chip-area	400 mm² (IGBT) + 200mm² (diode)	140 mm²	4.3x lower
Conduction losses* (W)	244.1	377.9	
Turn-on losses* (W)	105.1	24.1	> 4x lower
Turn-off losses* (W)	228.4	32.7	> 7x lower
Diode's conduction losses* (W)	45.9	Negligible	
Diode's Q_{rr} losses* (W)	99.5	Negligible	
(S1+D1) Total losses* (W)	**723**	**435**	40% lower
Junction Temperature (℃)	**142.8**	**162.6**	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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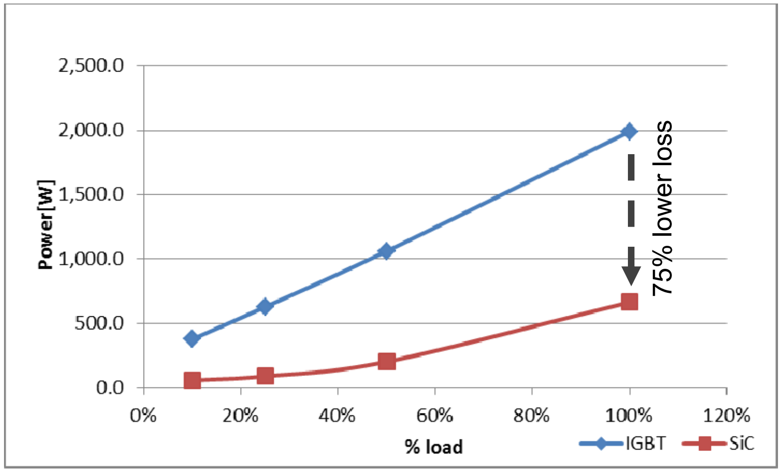
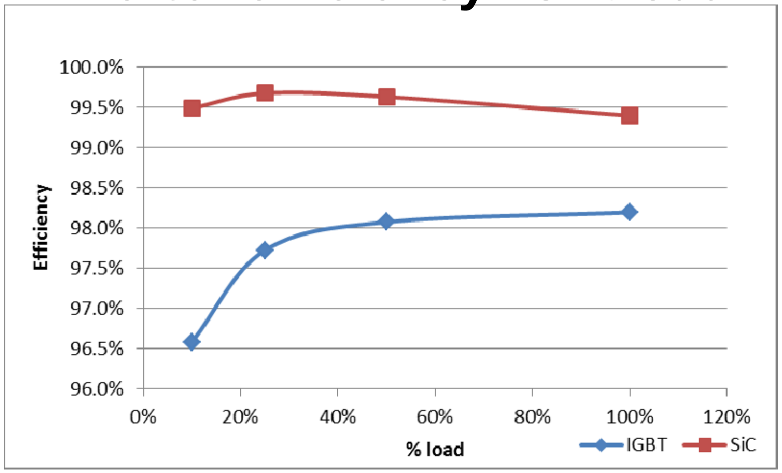
SiC Solution: Lower Losses, Higher Efficiency

f_{sw}=16kHz, Operating phase current up to 230A_{rms}

Inverter losses vs %load



Inverter efficiency vs %load



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

SiC shows much lower losses in the whole load range

SiC offers 1% higher efficiency or more over the whole load range!

Lower losses mean smaller cooling system and longer battery autonomy

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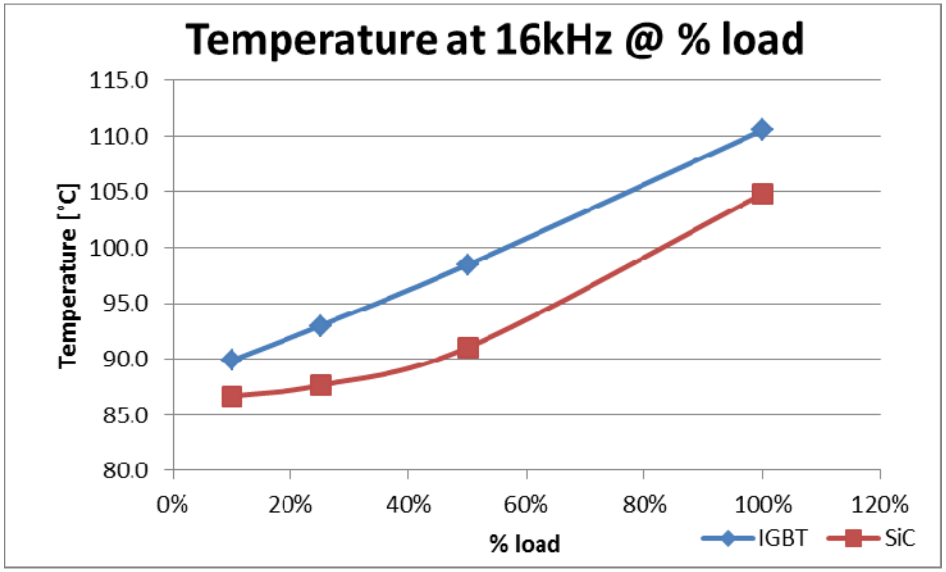
Remarks About Junction Temperature

Operating phase current up to $230A_{rms}$



- $R_{thJ\text{-}C(IGBT\text{-}die)}$=0.4℃/W;
- $R_{thJ\text{-}C(SiC\text{-}die)}$=1.25℃/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: 85℃ 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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80kW Traction Inverter Conclusions

This design example has shown that SiC MOSFETs can offer:

- More than 50% module/package size reduction
  - Much smaller semiconductor area giving ultra-compact solution
- >1% efficiency improvement (75% lower loss):
  - Much lower losses at low-medium load giving longer autonomy
- 80% cooling system downsize:
  - Lower losses at full load giving smaller cooling system
  - Lower ΔT (T_j-T_{fluid}) in the whole load range giving best reliability

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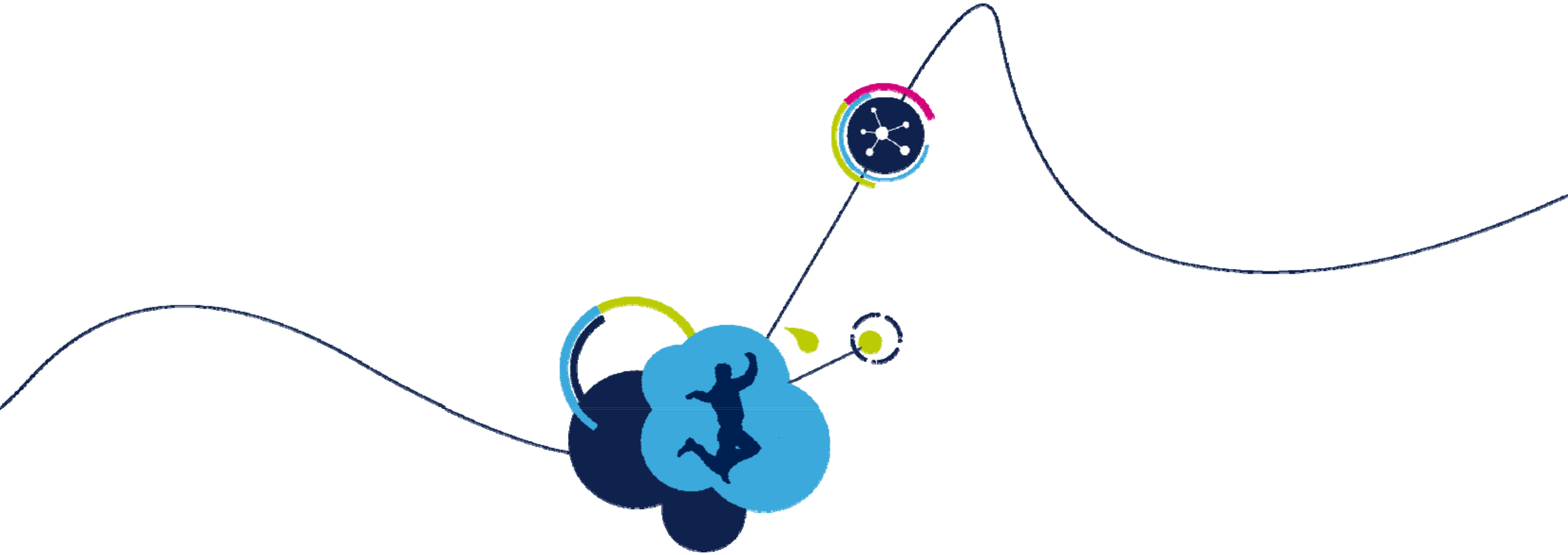

Conclusions

Component Cost Considerations

SCT30N120 (1200V/80mΩ,typ)

- Today
  - Price of SiC MOSFET is 4 - 5x relative to 1200V/45A silicon IGBT
- Near Term (2 – 3 years)
  - Price of 2 to 2.5x vs IGBT, cost reduction derived from increasing wafer diameter, improvements in $R_{DS(on)}$ x area FOM, and higher volume
- Long Term (5 – 10 years)
  - Continue to drive cost down by combination of device improvements, increased volume and larger wafer diameter

SiC MOSFET Price Roadmap

- Today SiC represents an attractive but still expensive solution for many applications
  - Even with the benefits of SiC technology, including higher efficiency, higher temperature operation and lower component count, in most cases the power electronics designer cannot afford SiC due to the cost

- Comparing the costs for transistors on the discrete level can be misleading, so it is recommendable to look at the cost of the entire system
  - It is possible to dramatically reduce the cost and size of cooling system and magnetics thanks to the very low switching losses of SiC. Thus power application designers are able to achieve higher efficiency while simultaneously reducing the overall system cost.

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Conclusion

- SiC MOSFET-based power converters now offer system level benefits compared to silicon IGBT-based solutions
  - As shown in the 80kW Inverter example, SiC offers reduced power dissipation, even while operating at the same switching frequency, giving higher efficiency, smaller cooling system requirements and overall reduced system cost
  - For systems where switching frequency can be adjusted, further benefits can be realized by use of SiC MOSFETs
- Today's SiC MOSFETs already show significant reduction in footprint compared to silicon solutions, this will continue as SiC MOSFET development continues to advance.
- As SiC MOSFETs become more widely adopted, higher volumes will further drive down cost and continue to displace silicon power transistors.

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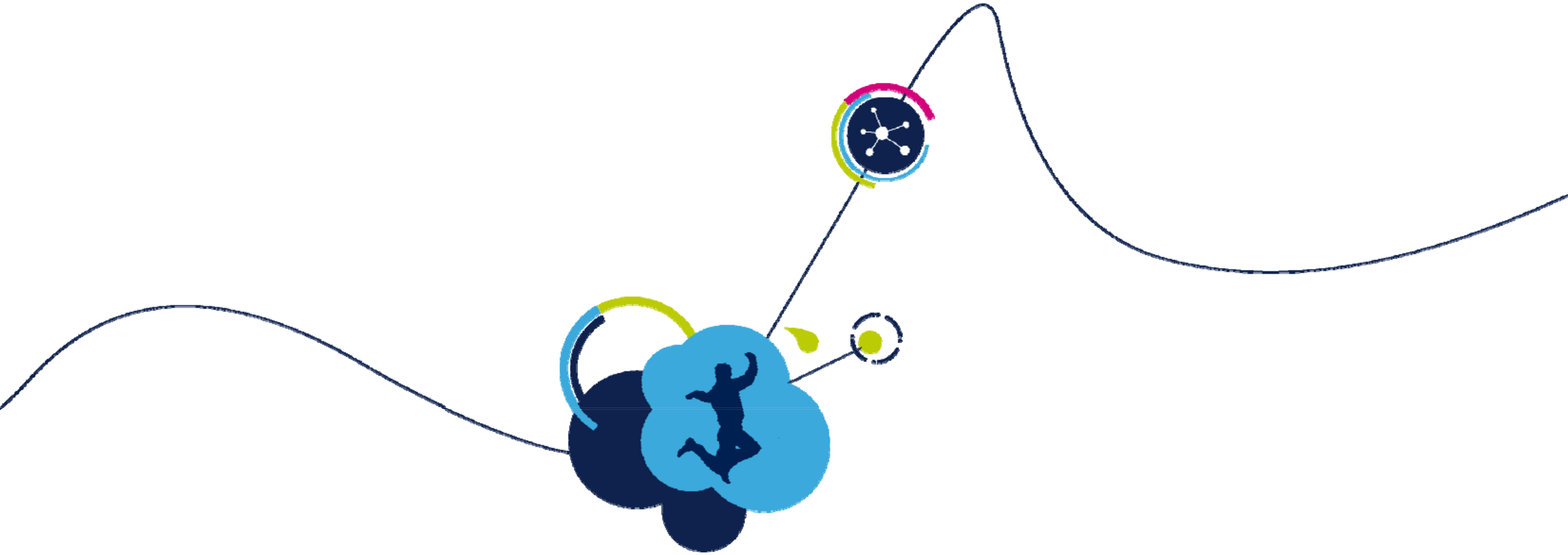

Thank You!