SILICON CARBIDE (SIC) SEMICONDUCTORS FOR (X)EV ARE GETTING CLOSER TO REALITY

Dr. Andre Christmann, Infineon Technologies

SAE INTERNATIONAL®

Infineon

Content

1 Silicon Carbide at Infineon

2 Silicon Carbide in automotive

Challenges

The system benefits of SiC

3 Why is SiC now closer to Reality?

4 Next generation of power module

Corporate Social Responsibility
We create a net ecological benefit

Emission Reduction enabled by our products and solutions

around 1.4 million tons CO_2 equivalents

around 58.2 million tons CO_2 equivalents

CO_2 burden[1)]

Ratio around 1:41

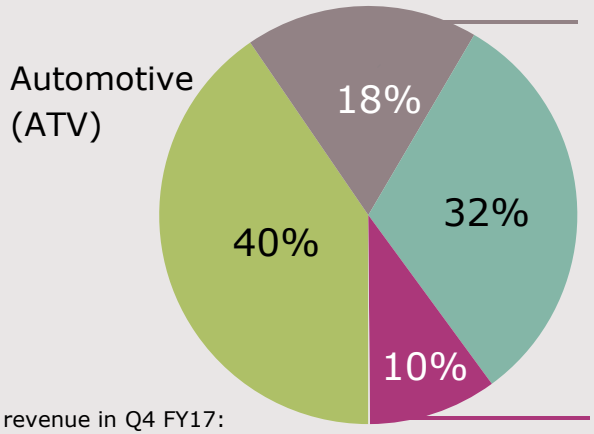
CO_2 savings[2)]

Net ecological benefit:
CO_2 emissions reduction of more than 56 million tons

1) This figure considers manufacturing, transportation, function cars, flights, materials, chemicals, water/wastewater, direct emissions, energy consumption, waste, etc. and is based on internally collected data and externally available conversion factors. All data relate to the 2017 fiscal year.
2) This figure is based on internally established criteria, which are explained in the explanatory notes. The figure relates to the calendar year 2016 and considers the following fields of application: automotive, LED, induction cookers, PC power supply, renewable energy (wind, photovoltaic), mobile phones' chargers as well as drives. CO_2 savings are calculated on the basis of potential savings of technologies in which semiconductors are used. The CO_2 savings are allocated on the basis of the Infineon market share, semiconductor content and lifetime of technologies concerned, based on internal and external experts' estimations. Despite the fact that CO_2 footprint calculations are subject to imprecision due to the complex issues involved, the results are nevertheless clear.

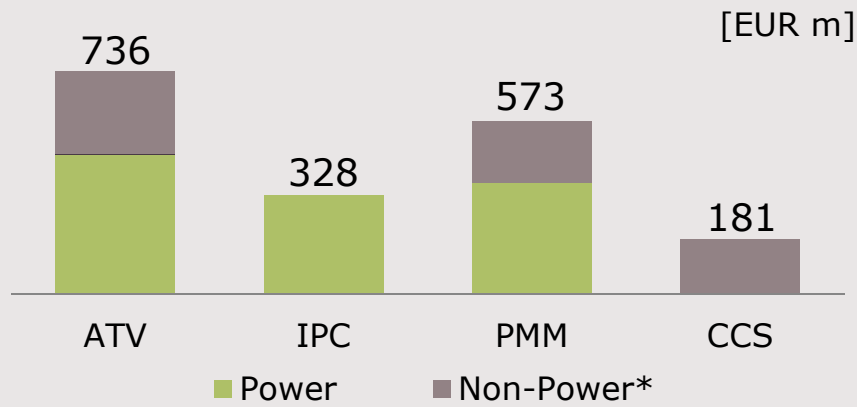
Infineon at a glance

Business Segments



revenue in Q4 FY17:
€1,820m incl. OOS and C&E of €2m

Power represents ~60% of revenue



*embedded control, RF, sensors

Market Position

Automotive	Power	Smart card ICs
		
# 2	**# 1**	**# 1**
Strategy Analytics, April 2017	IHS Markit, Technology Group, August 2017	IHS Markit, Technology Group, July 2017

Synergy

Power & Automotive

The energy conversion from the DC battery
to an AC electrical motor
is done by an Inverter
driven by MOSFETs,
IGBTs or Silicon Carbide switches

Product range

Automotive (ATV)

- 32-bit automotive microcontrollers for powertrain, safety and driver assistance systems
- **Discrete power semiconductors**
- **IGBT modules**
- Industrial microcontrollers
- Magnetic and pressure sensors
- Power ICs
- Radar
- Transceiver (CAN, LIN, Ethernet, Flex Ray™*)
- Voltage regulators

Industrial Power Control (IPC)

- Bare die business
- **Discrete IGBTs**
- Driver ICs
- **IGBT modules (high-power, medium-power, low-power)**
- IGBT module solutions incl. IGBT stacks

Power Management & Multimarket (PMM)

- Control ICs
- Customized chips (ASICs)
- Discrete low-voltage and high-voltage power transistors
- GPS low-noise amplifier
- Low-voltage and high-voltage driver ICs
- MEMS and ASICs for silicon microphones
- RF antenna switches
- RF power transistors
- TVS (transient voltage suppressor) diode

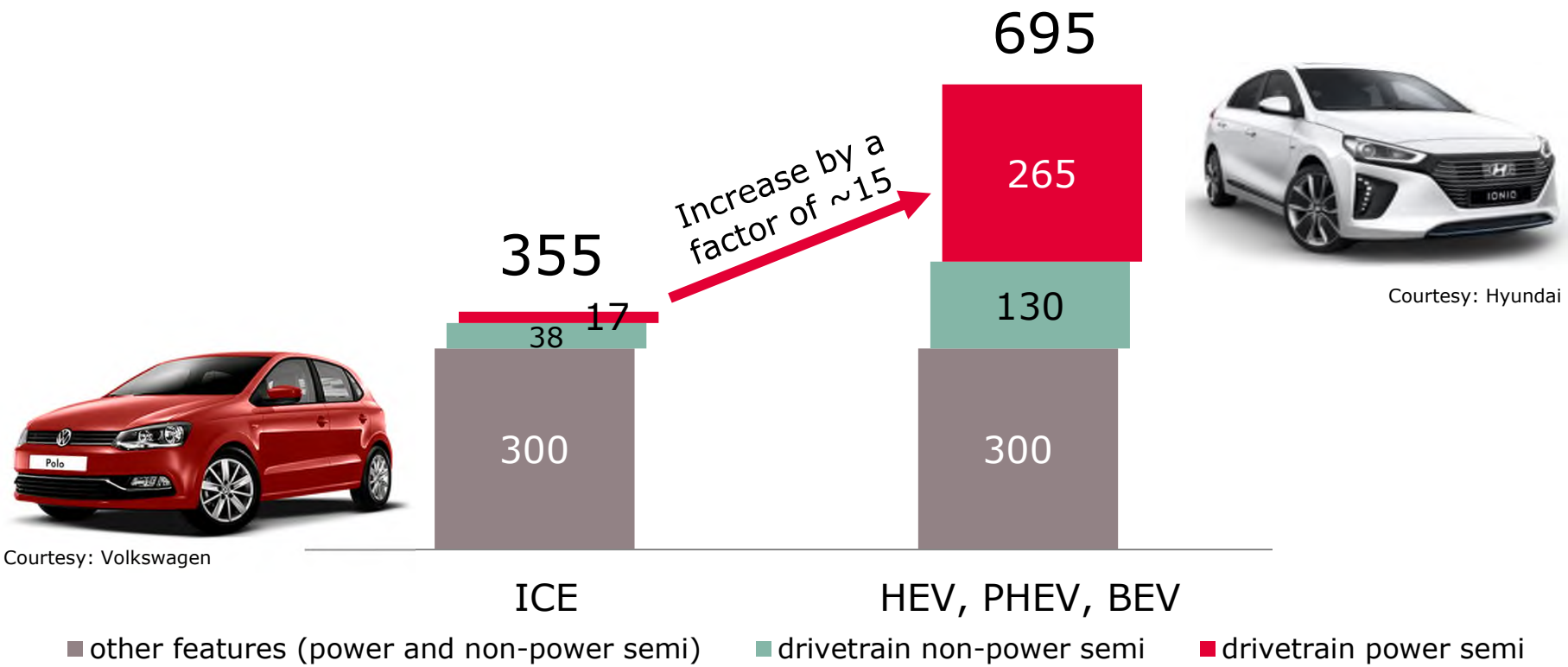
Chip Card & Security (CCS)

- Contact-based security controllers
- Contactless security controllers
- Dual-interface security controllers (contact-based and contactless)

With the transition from ICE to xEV the power semi content in powertrain increases by ~15x

Average semiconductor content by type of car

[USD]



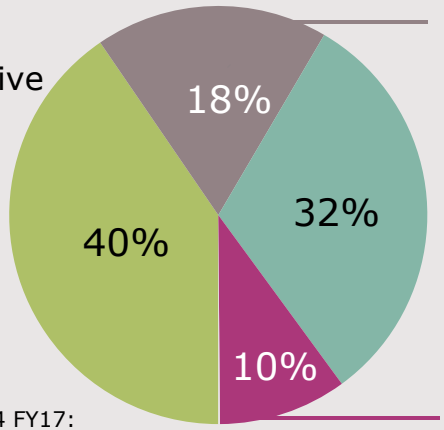
Courtesy: Hyundai

Courtesy: Volkswagen

Source: Strategy Analytics, "Automotive Semiconductor Content", May 2017; Infineon

Infineon at a glance
1 in Power

Business Segments



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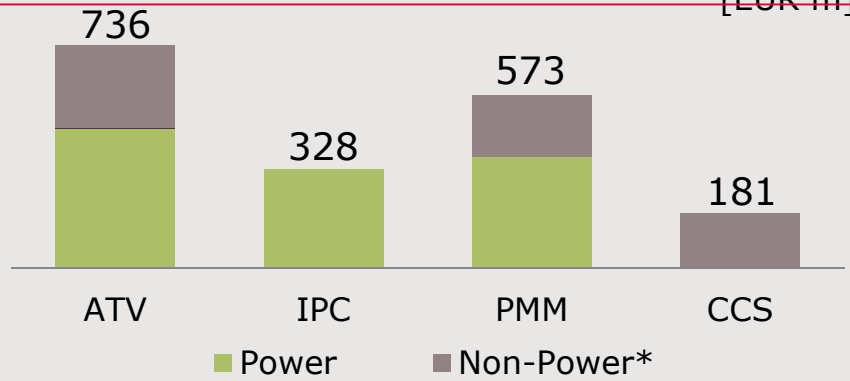

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is done by an Inverter
driven by MOSFETs,
IGBTs or Silicon Carbide switches

Infineon builds up on **25 years of experience** in SiC technology

+SiC

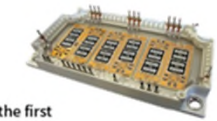
1992
Start of power device development, SiC diodes and transistors for high power industrial applications

1998
Start of 2" wafer technology integration in the high volume silicon power manufacturing line of Infineon

2001
Worldwide first release of commercial SiC power devices

2006
Release of 2nd generation diodes based on Infineon's unique MPS principle

2006
Release of the first power modules with SiC devices inside for industrial motor drive applications (hybrid modules)



2007
Move to 3" wafer production

2008
Release of 3rd diode generation with improved thermal properties

2009
Release of first high power module with SiC Diodes

2010
Move to 100 mm 4" wafer diameter

2012
Roll out of SiC portfolio for solar power string inverters

2013
Release of 5th generation of diodes, introduction of thin wafer manufacturing for SiC

2014
Commercial release of Infineon's ultra reliable SiC JFET switch

2014
Extension of the 5th generation principle towards 1200 V diodes

2015
Start of 150 mm conversion in manufacturing

2016
Technology launch of CoolSiC™ MOSFET at the PCIM in Nuremberg

2017
Commercial release of CoolSiC™ MOSFET lead products in power modules and discrete versions

 # 1
in Power

Infineon is one of the few players with a **long track record** in **Silicon & Silicon Carbide**

Infineon builds up on 25 years of experience
Increase of wafer size over time

+SiC

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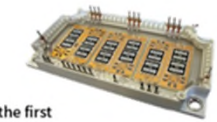

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2016
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1998

2″ 

3″ 

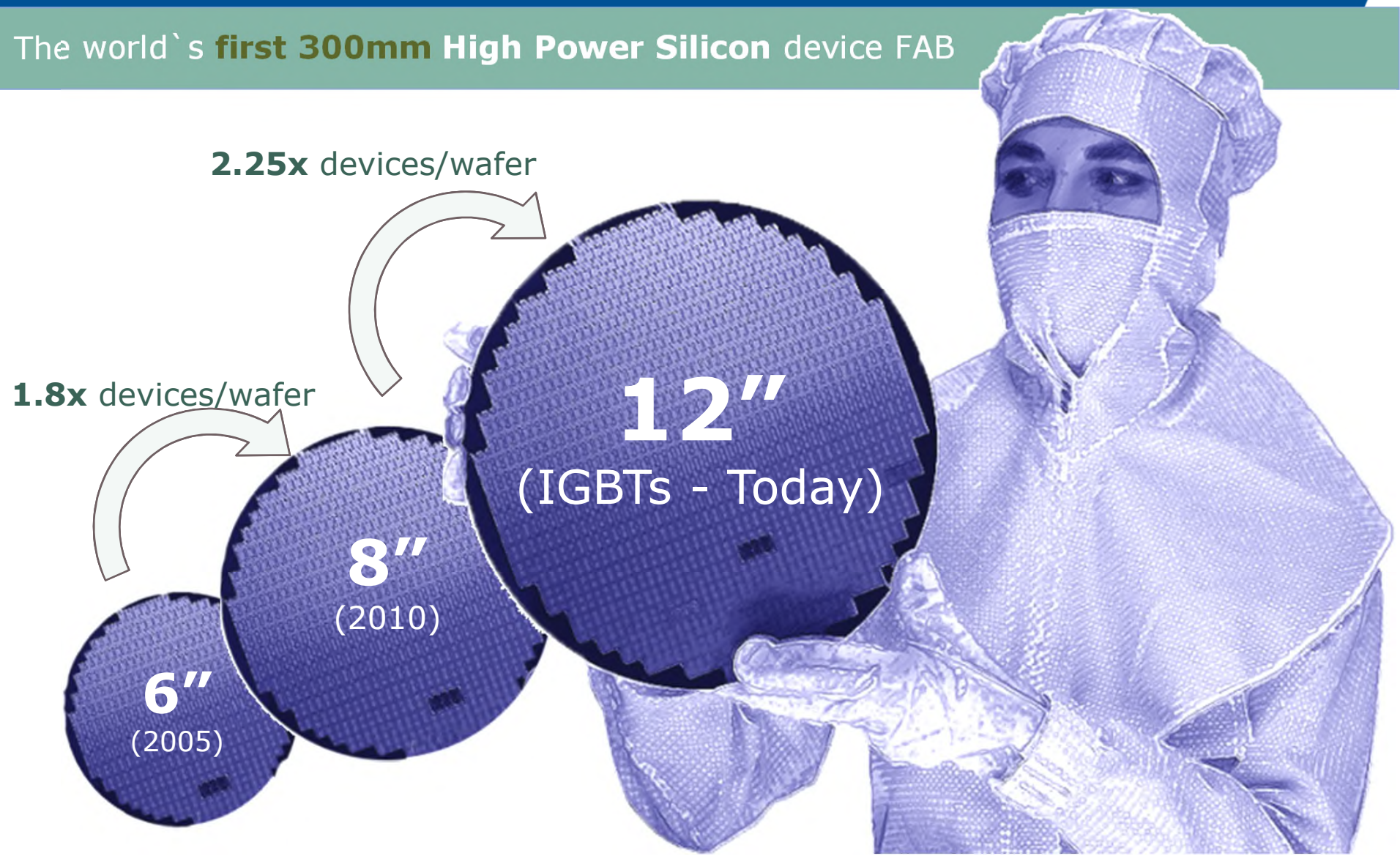
4″

2015

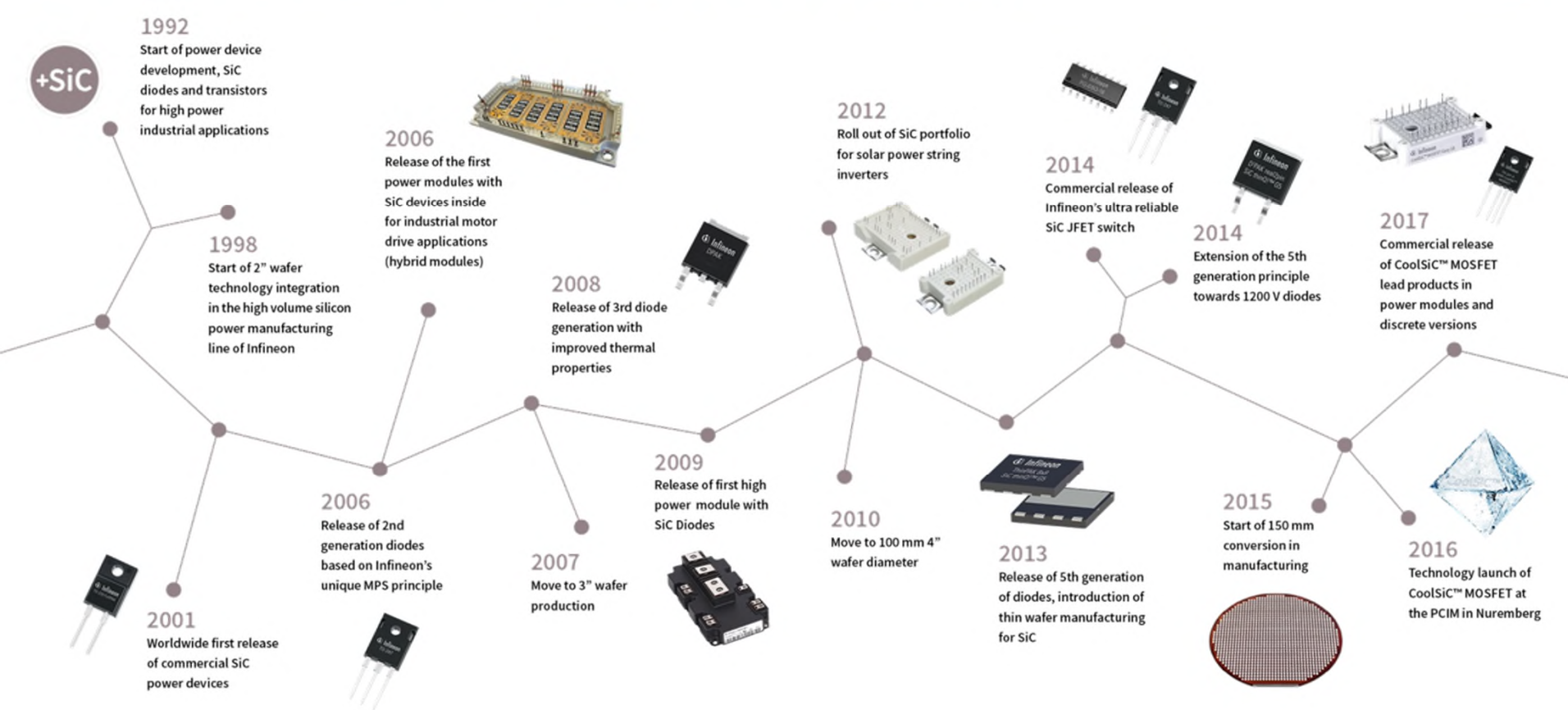
150mm
6″

Lower the cost
Economies of Scale for IGBTs

The world`s **first 300mm High Power Silicon** device FAB



Infineon builds up on 25 years of experience
Increase of package/product portfolio



Switch Vertical JFET Trench MOSFET

Evolution in industrial portfolio

Diode Gen1 Gen2 Gen3 Gen5

Content

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Challenges

The system benefits of SiC

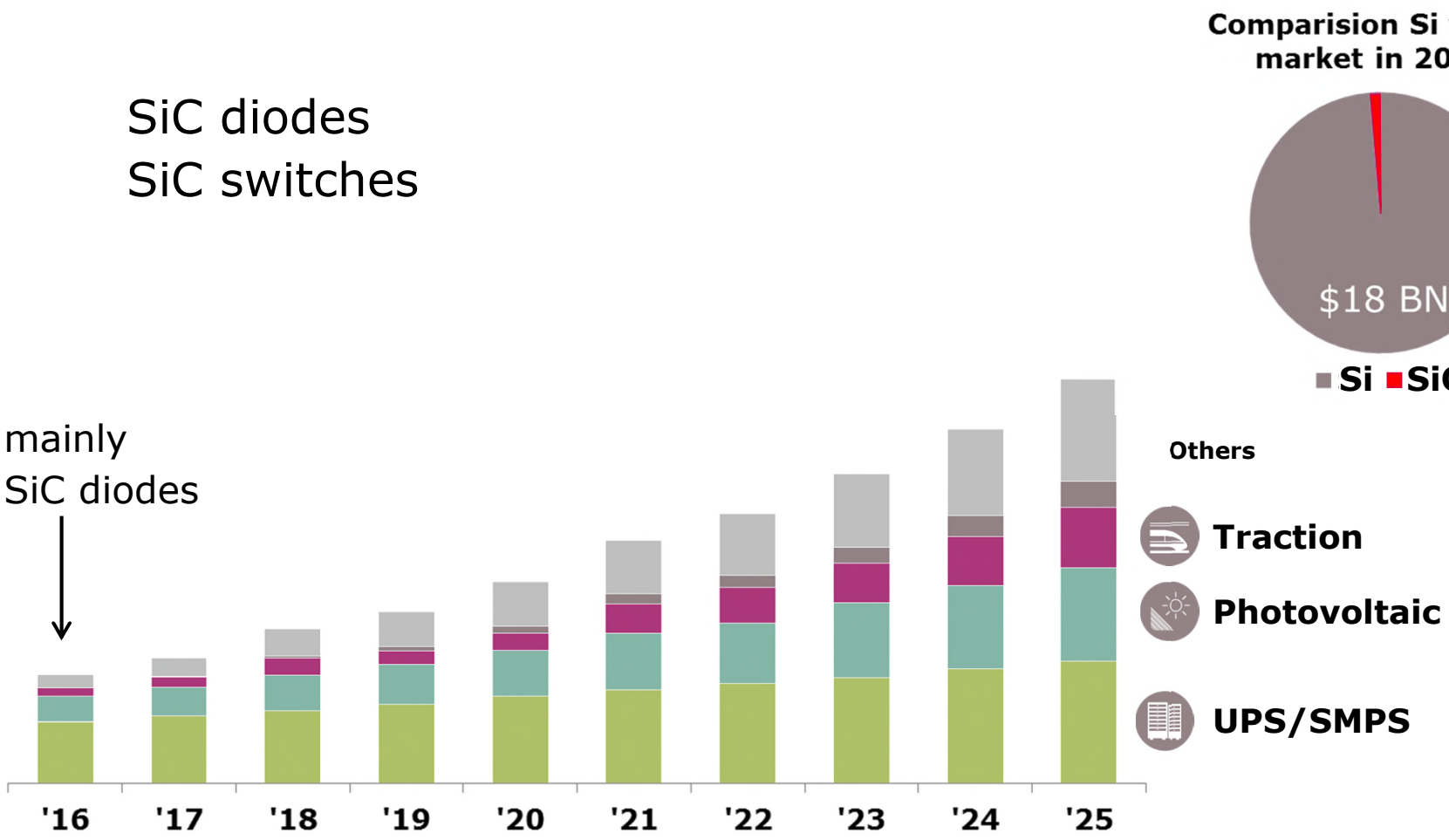
3 Why is SiC now closer to Reality?

4 Next generation of power module

We expect extraordinary growth for SiC, more applications will start the adoption

SiC Power market development

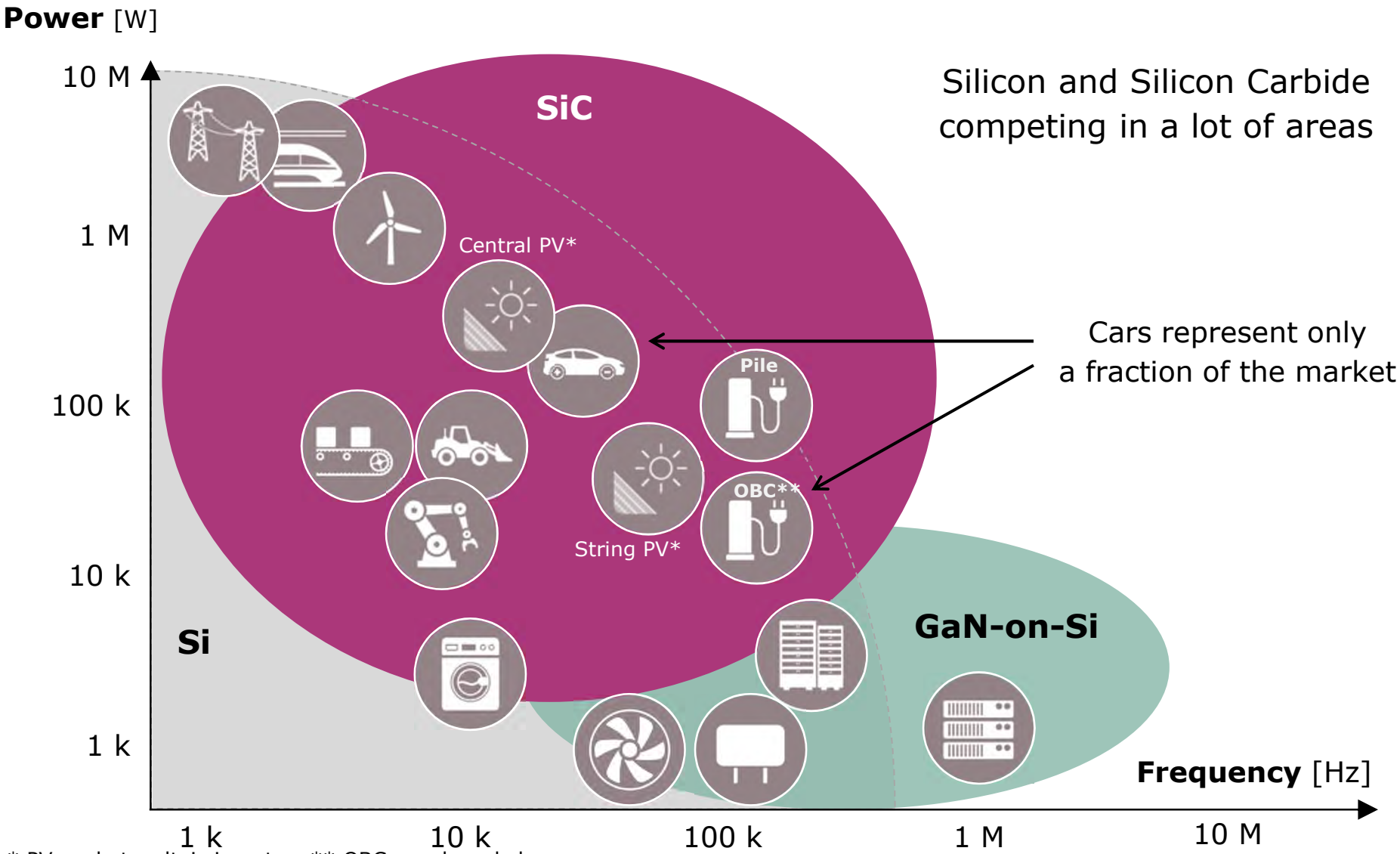
SiC diodes
SiC switches



Sources: IHS Markit, "World Market for SiC and GaN Power Semiconductors", Feb 2016

UPS = uninterrupted power supply; SMPS = Switched-mode power supply

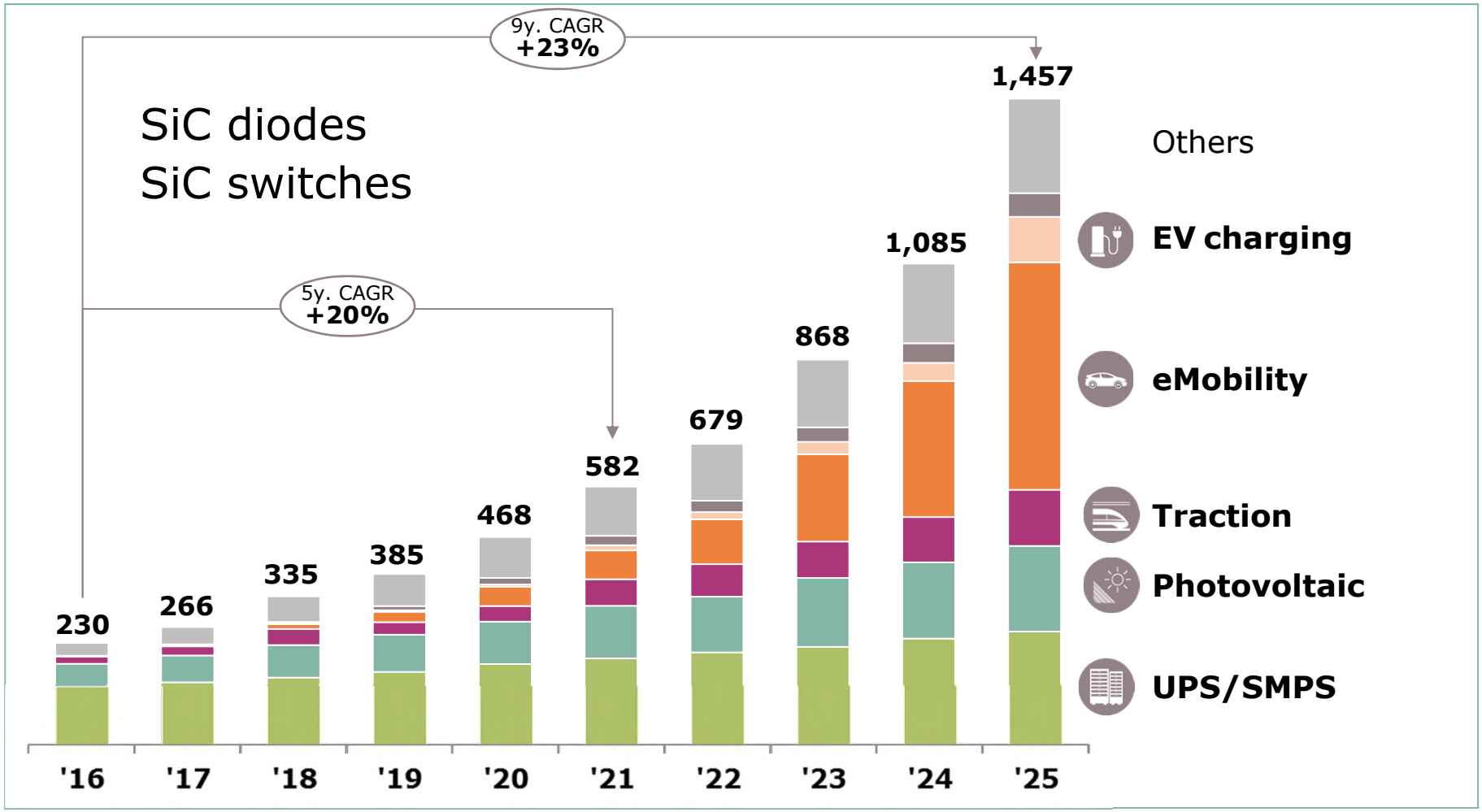
SiC and GaN enable higher efficiency through faster switching at lower losses than Si



* PV = photovoltaic inverter; ** OBC = onboard charger

We expect extraordinary growth for SiC, > 20% Compound Annual Growth Rate

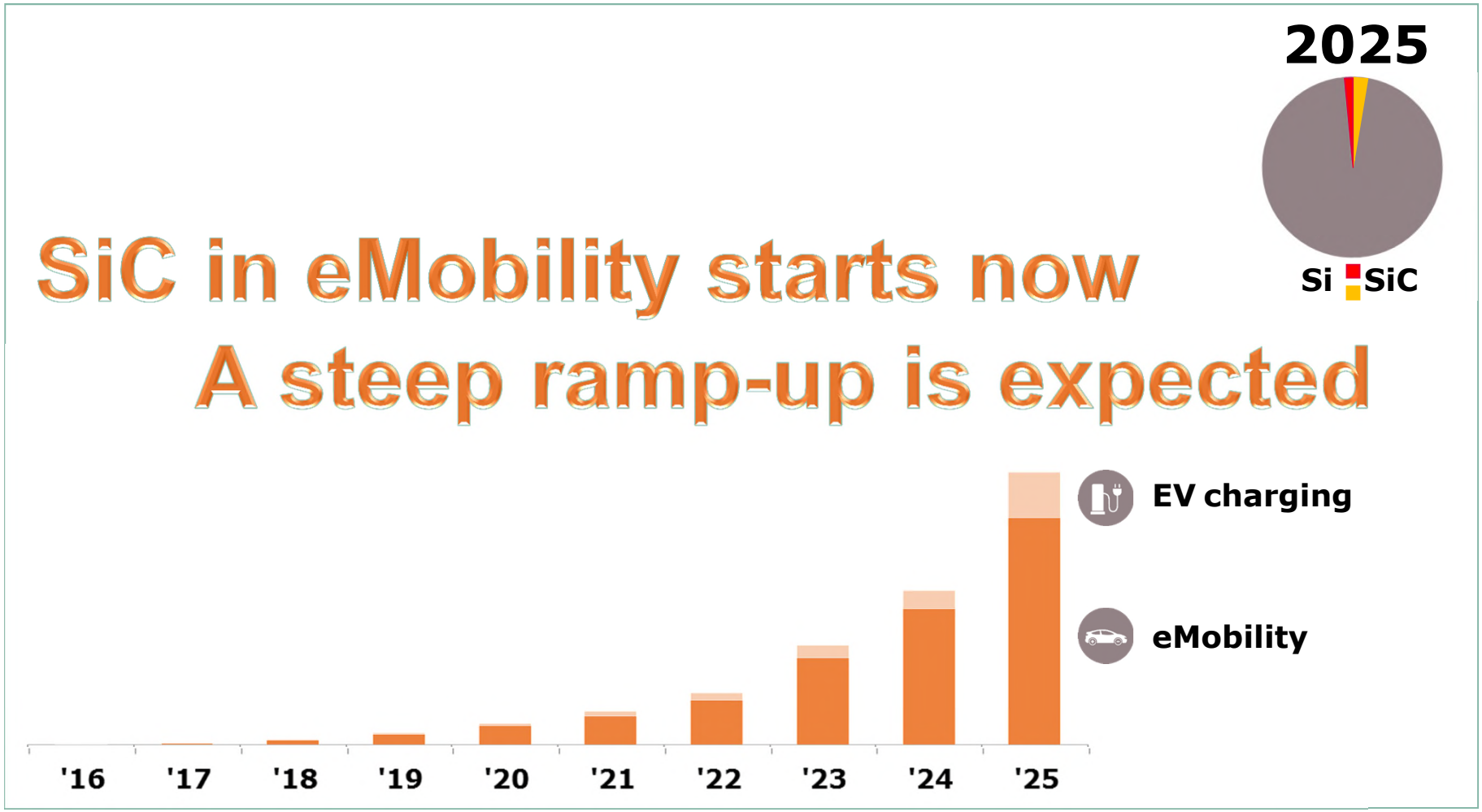
SiC Power market development [m USD]



Sources: IHS Markit, "World Market for SiC and GaN Power Semiconductors", Feb 2016

We expect extraordinary growth for SiC in eMobility and charging

SiC Power market development

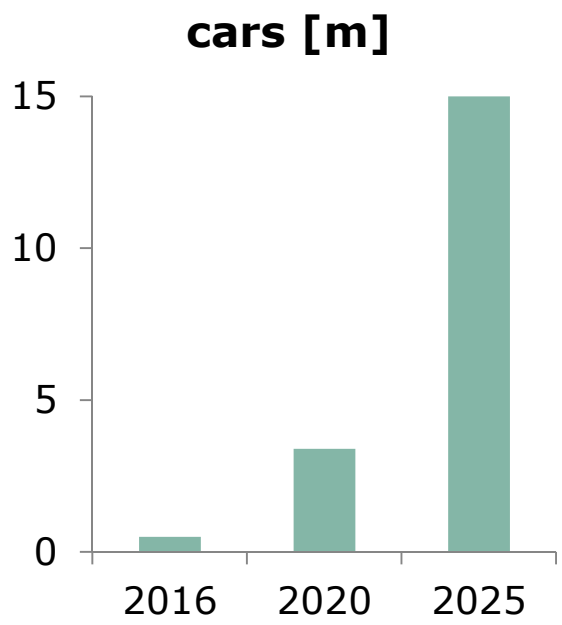


Sources: IHS Markit, "World Market for SiC and GaN Power Semiconductors", Feb 2016

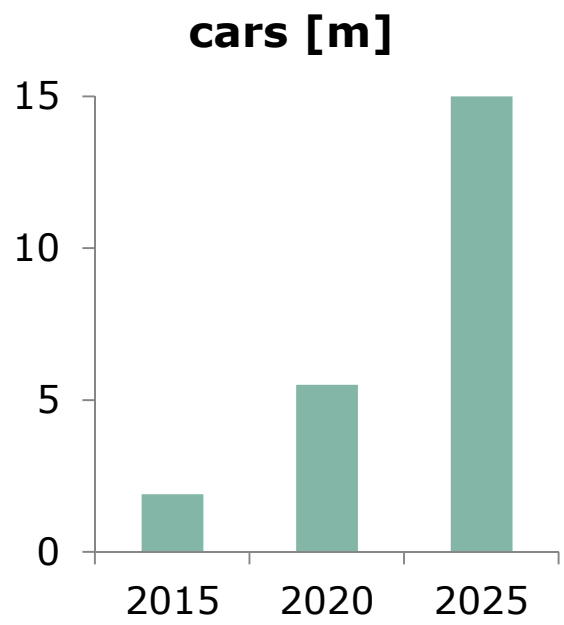
What is the Growth Driver ?

10M BEVs in 2025

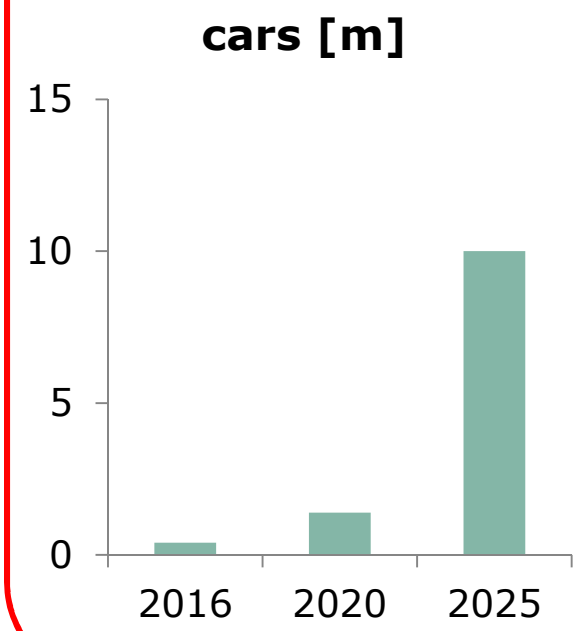
Mild hybrid / 48 V



PHEV / HEV



BEV



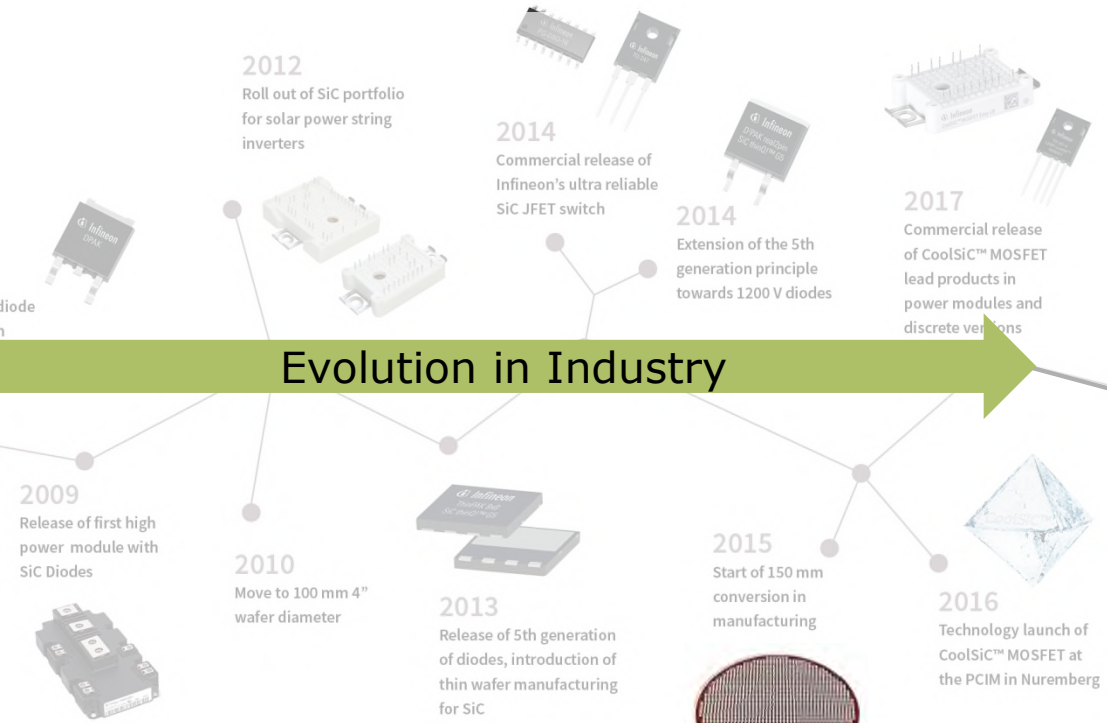
Source: IHS Automotive, "Alternative Propulsion Forecast", January 2017

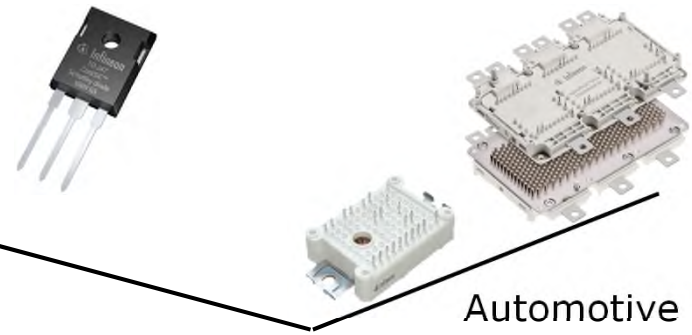
Infineon builds up on 25 years of experience
Evolution: Entering the automotive Market

Gen 4
diode

Gen 5
diode

Automotive
SiC diode
Gen 5 = 1st automotive product





Evolution in Industry

Automotive
SiC MOSFET

Automotive
Power module
SiC MOSFET

6'' Prerequisite for Infineon automotive products

Roll-out Automotive

Brief recapitulation

- Trends
  - **Growing market share** of SiC products
  - **Steep increase of SiC** in automotive applications
  - **10 Million BEV** in **2025**

- Infineon
  - **150 mm Wafer** in SiC production line established
  - First automotive qualified products in **2018**
  - **SiC MOSFET** design based on **Trench Technology**

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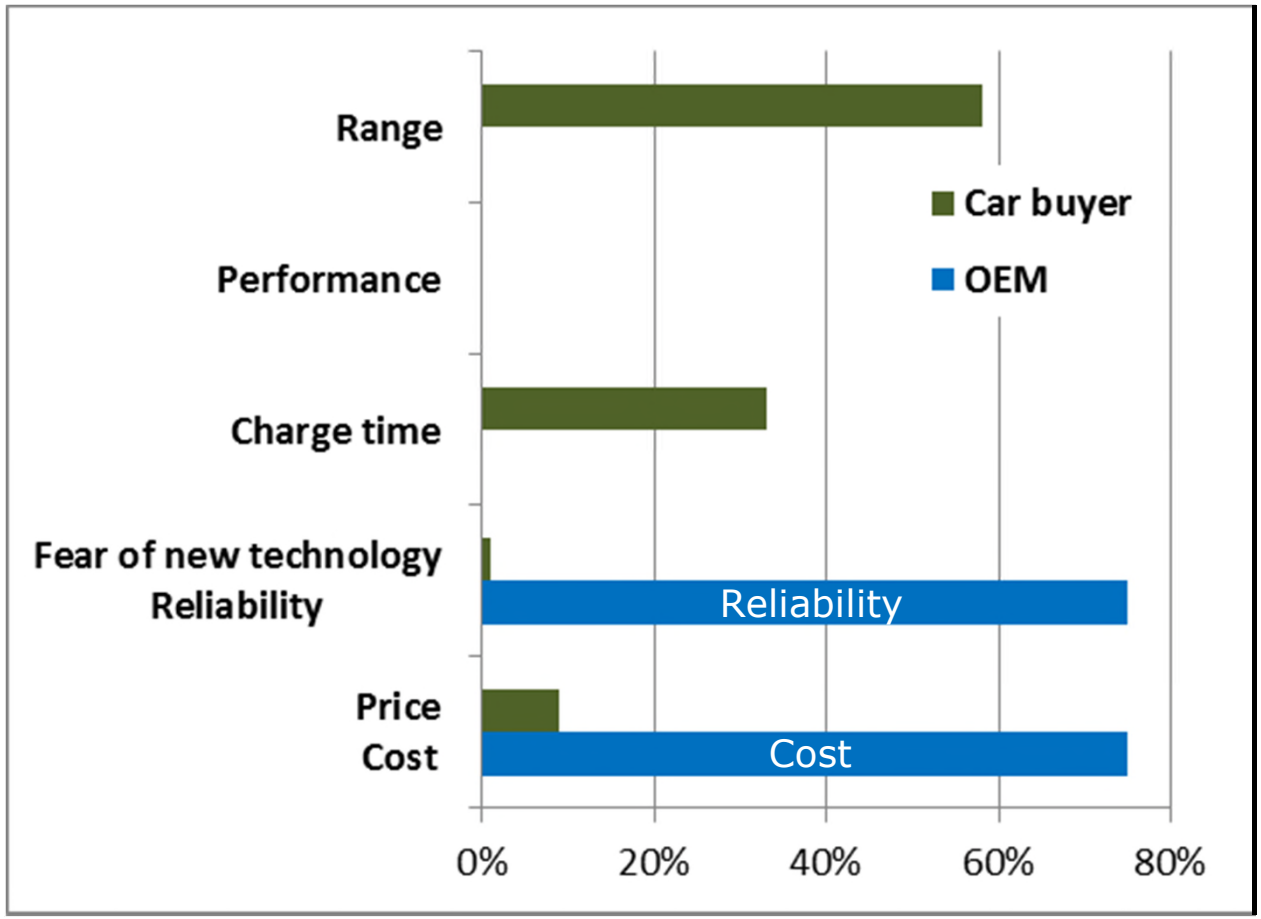
Recent Infineon public poll on xEV adoption

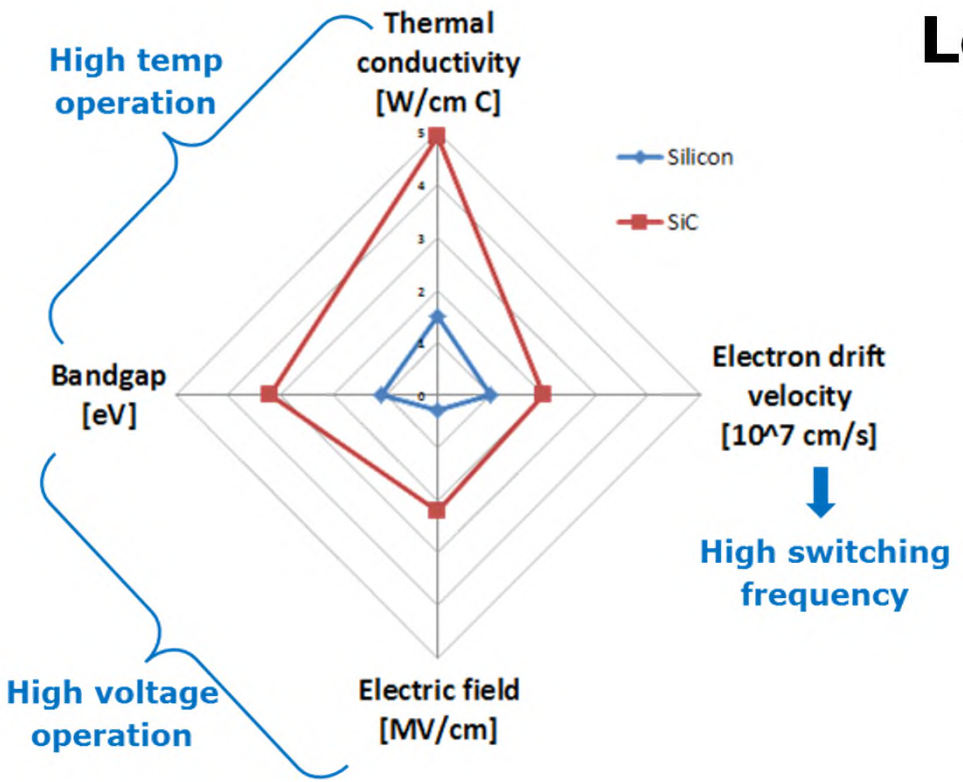
Car buyer: What are the barriers to xEV adoption?

OEMs: What are the barriers to SiC adoption?



Wide **B**and **G**ap could be a game changer
Comparison of physical properties

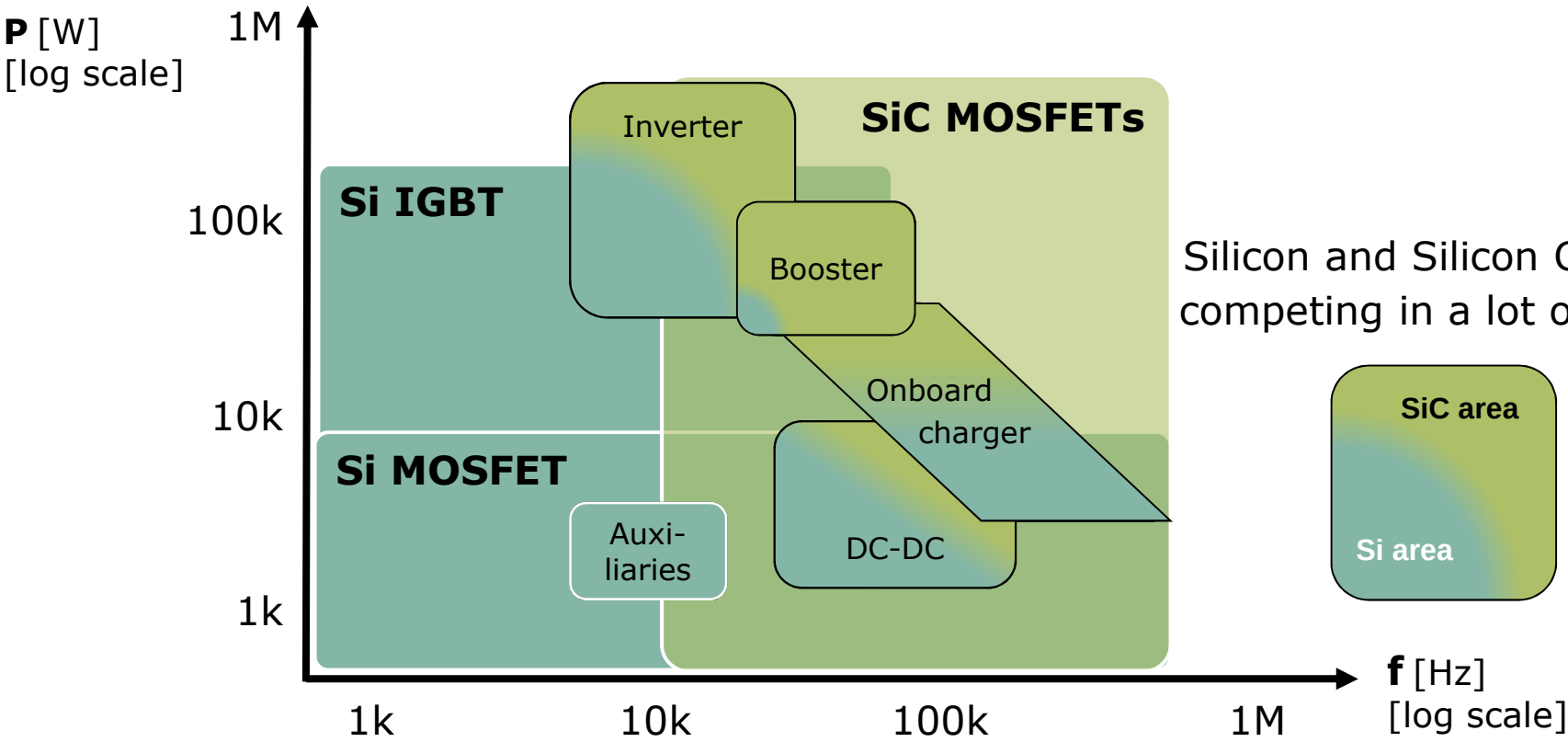
› Advantages of WBG materials



Low losses even at high switching frequencies & high voltages

Technology fit: SiC is the option of choice for most demanding xEV subsystems

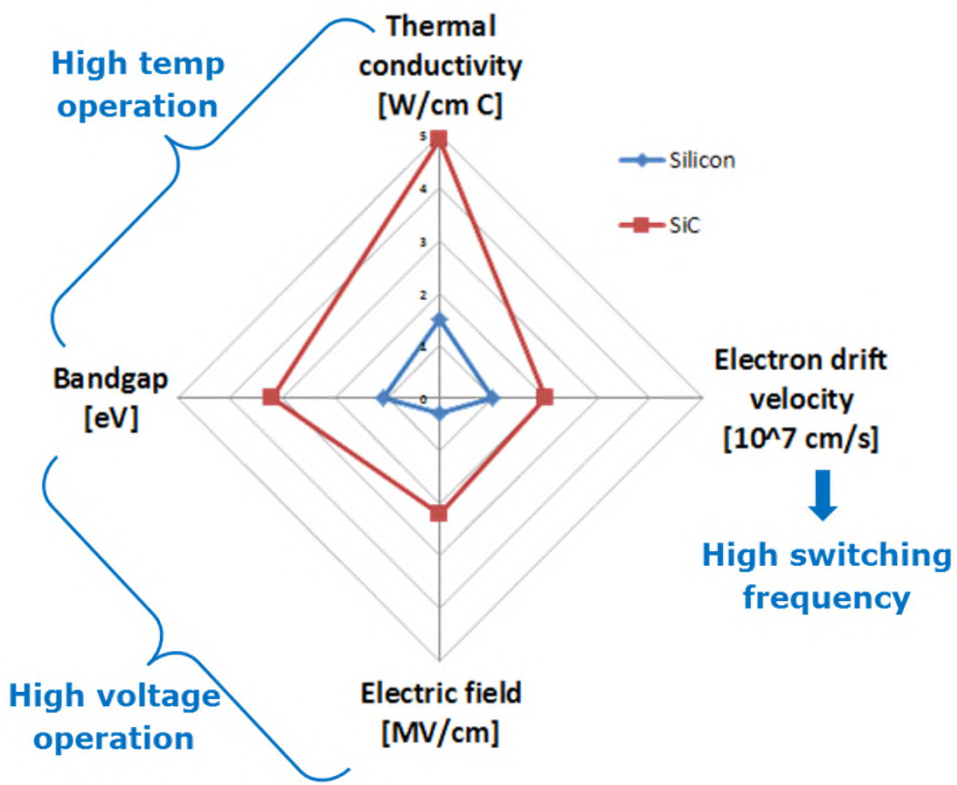
Sweet spots for SiC-based xEV subsystems



Advancements in SiC technology will penetrate more and more xEV subsystems over the course of the next years

Wide **B**and **G**ap could be a game changer
Superior but comes with some disadvantages

› Advantages of WBG materials



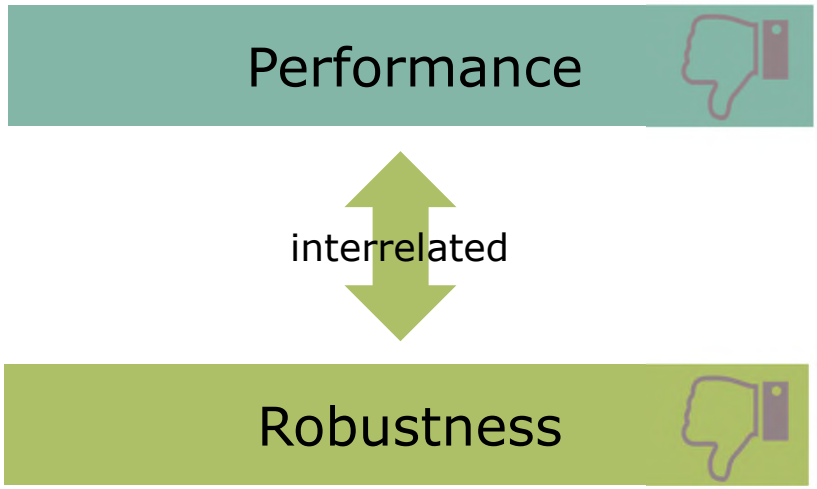
› Disadvantages in SiC

- **Defects @ interface Gate Oxide – SiC**
  - Deteriorated e^- transport
  - "weakening" of Gate Oxide
- **Manufacturing cost**
  - Higher Wafer cost
  - Higher defects density
  - Lower yields

GOX: Gate Oxide – thin insulating layer for control of the device, most sensitive part of the device

Silicon Carbide - Oxide Robustness
Reduced Robustness & reduced Performance

A **thick oxide** reduces the performance



› Disadvantages in SiC

- **Defects @ interface Gate Oxide – SiC**
- Deteriorated e^- transport
- "weakening" of Gate Oxide

Countermeasure **thick oxide**

- lower failure rate for extrinsic defects
- lower electrical fields across GOX
- efficient screening (higher voltages)

GOX: Gate Oxide – thin insulating layer for control of the device, most sensitive part of the device

Silicon Carbide - Oxide Robustness
Reduced Performance

Performance 

Countermeasure
Trench Technology
- Less defects at vertical interface
- Higher electron mobility in “z-axis”

› Disadvantages in SiC
  – **Defects @ interface Gate Oxide – SiC**
    – Deteriorated e^- transport
    – “weakening” of Gate Oxide

Reliability – Oxide Robustness
Planar MOS vs. Trench MOS

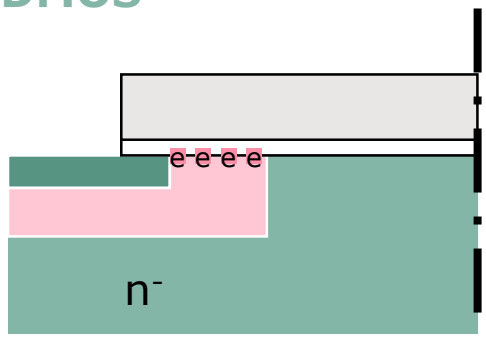
Channel Resistance (due to μ_{cha})

high

Channel Resistance (due to μ_{cha})

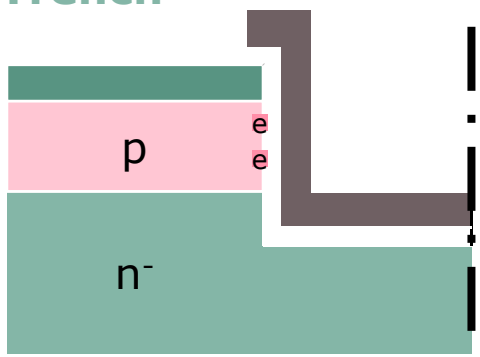
low

DMOS



High density of defects in the so called channel region

Trench



One order of magnitude **lower defect density** in channel region

Plus better outlook regarding cell shrinking as proven in Si technology

Silicon Carbide
Planar MOS vs. Trench MOS

Performance

Countermeasure
Trench Technology
- Less defects at vertical interface
- Higher electron mobility in “z-axis”

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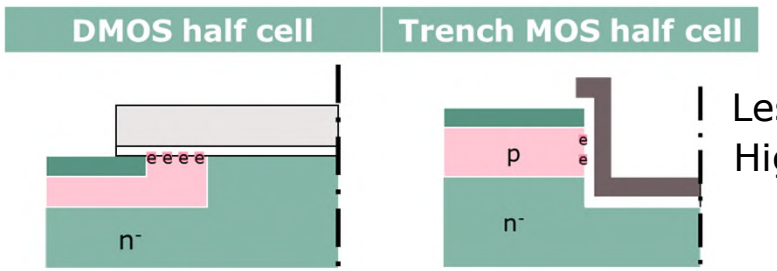


Less defects in vertical Trench
Higher e^- mobility in vertical Trench

Trench Technology

Channel Resistance (due to μ_{cha})	high		low
GOX Field on-state	low		low
GOX Reliability	high		high

Performance

Robustness

Reliability – Oxide Robustness
Planar MOS vs. Trench MOS

Performance

Countermeasure (?)
- Increase electrical field
  - higher Gate Voltage
  - lower Threshold Voltage
  - thin Gate Oxide

interrelated

Robustness

› Disadvantages in SiC

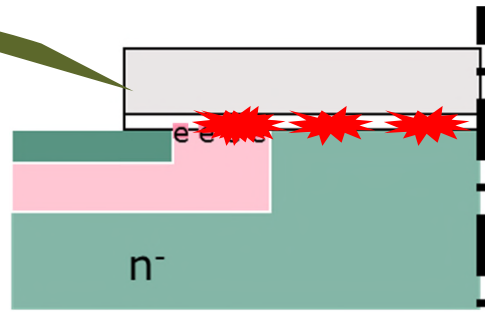
– **Defects @ interface Gate Oxide – SiC**

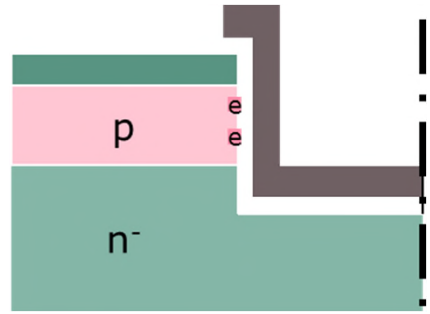
– Deteriorated e^- transport

– "weakening" of Gate Oxide

SiC MOSFET concepts
Performance / Robustness trade-off

Countermeasure (?): Increase electrical field
- higher Gate Voltage





		DMOS half cell	Trench MOS half cell
Channel Resistance (due to μ_{cha})		low	low
GOX Field on-state		high	low
GOX Reliability		low	high

A balanced approach is needed
Performance / Robustness trade-off

Performance	Robustness
$R_{DS(on)}$ A	Threshold Voltage
	Gate Oxide Thickness
	Cosmic Ray
	Short Circuit

Zero defect

Thick Gate Oxide

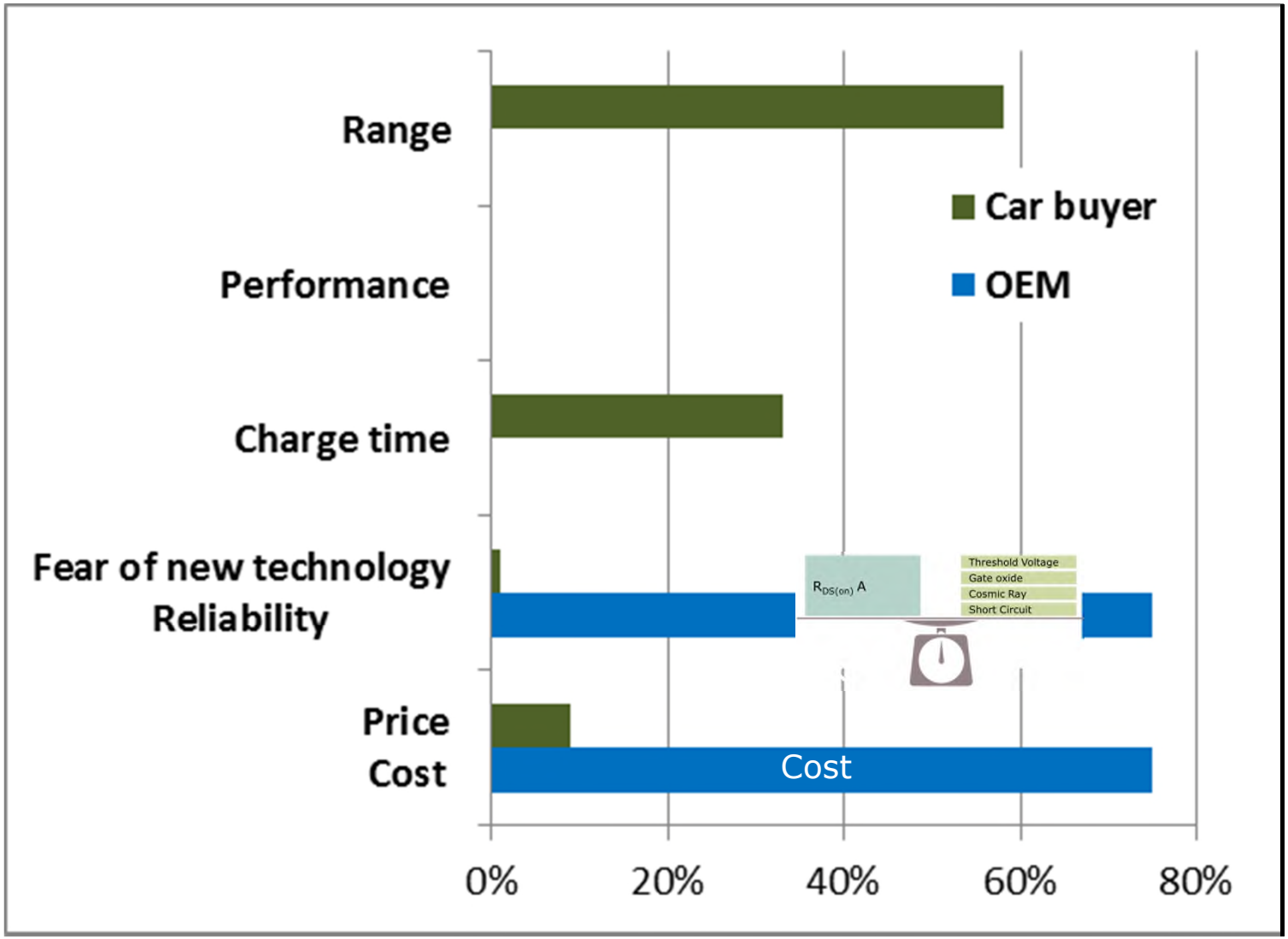
Trench Design

Infineon`s design target: **SiC** shall meet the same level of **quality and reliability as** state of the art **IGBT**

Recapitulation

- **Reliability** Challenge: Defect density and Gate Oxide Robustness
  - **Wafer quality** improving significantly
  - Infineon`s SiC MOSFET design based on **Trench Technology** and long time experience enables the **reduction of fit rates**

SiC addresses several obstacles
Reliability needs balanced approach

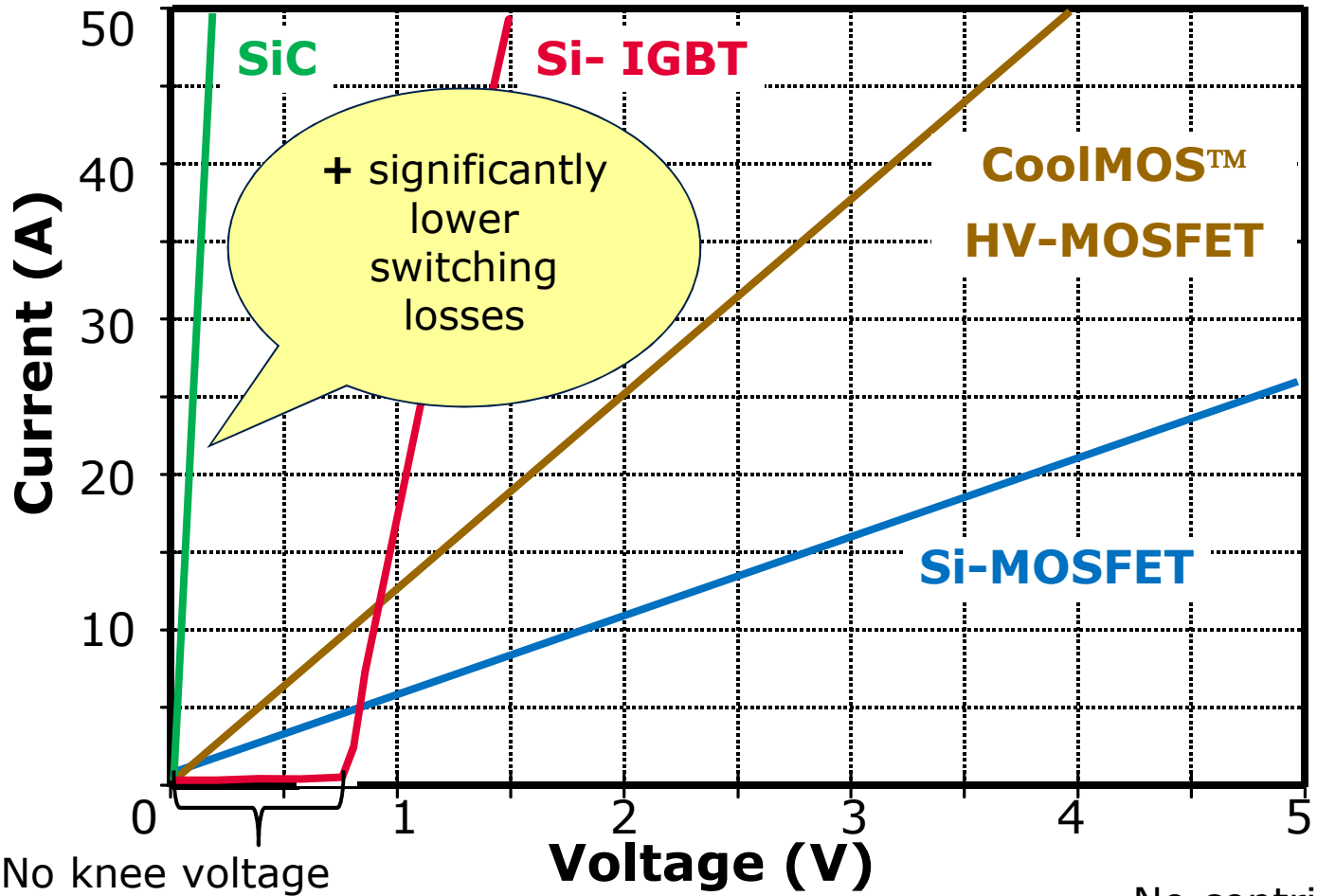


Agenda

1. Silicon Carbide at Infineon
2. Silicon Carbide in automotive
   - Challenges
   - The system benefits of SiC
3. Why is SiC now closer to Reality?
4. Next generation of power module

Benefits of SiC MOSFET
Reduction of dynamic AND static losses

› Power losses for a 1cm² semiconductor at 1000V and 50A



<200W
75W
200W
500W

$$P_{static} = v_{CE}(i) \cdot i_C(t)$$

No knee voltage
-> Reduced static losses especially at low currents

No contribution from **slow ions**
-> Reduced switching losses

Power density and efficiency in Traction Inverters are drivers for SiC in automotive

SiC performance improvements

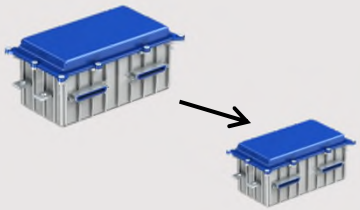
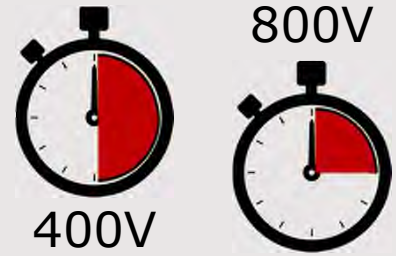
Loss reduction

Higher voltage

Power density

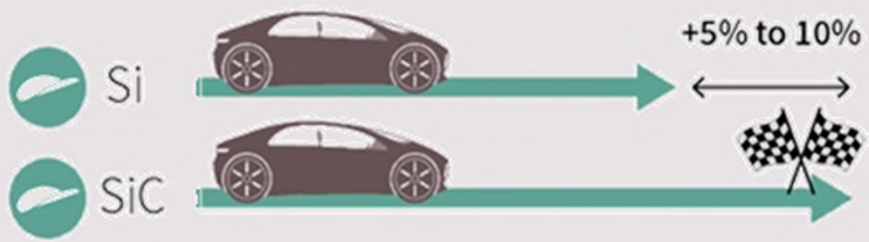
Efficiency

Higher power

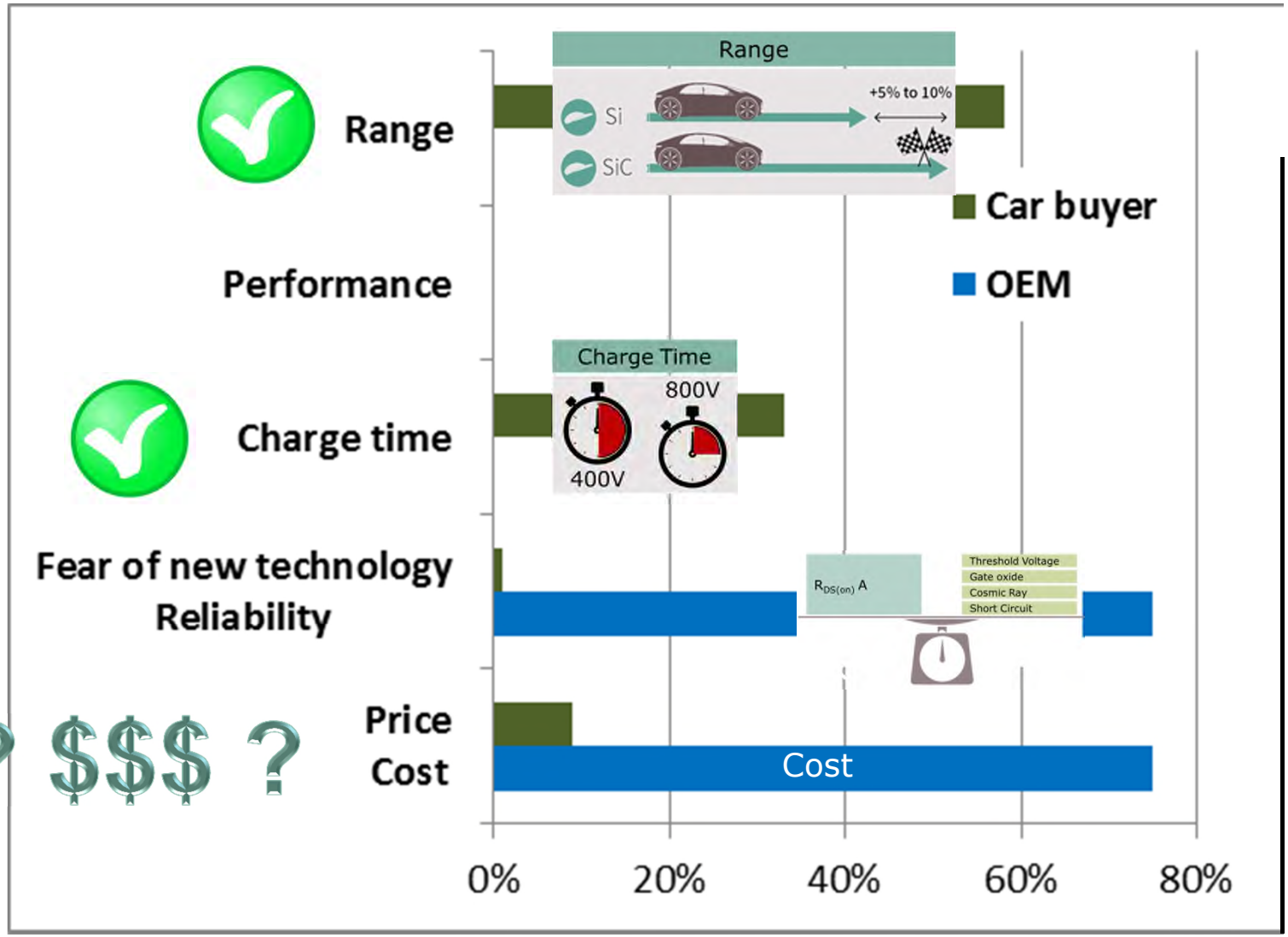
System size	More Power	Battery size	Charge Time
			

Faster 0–60 mph time

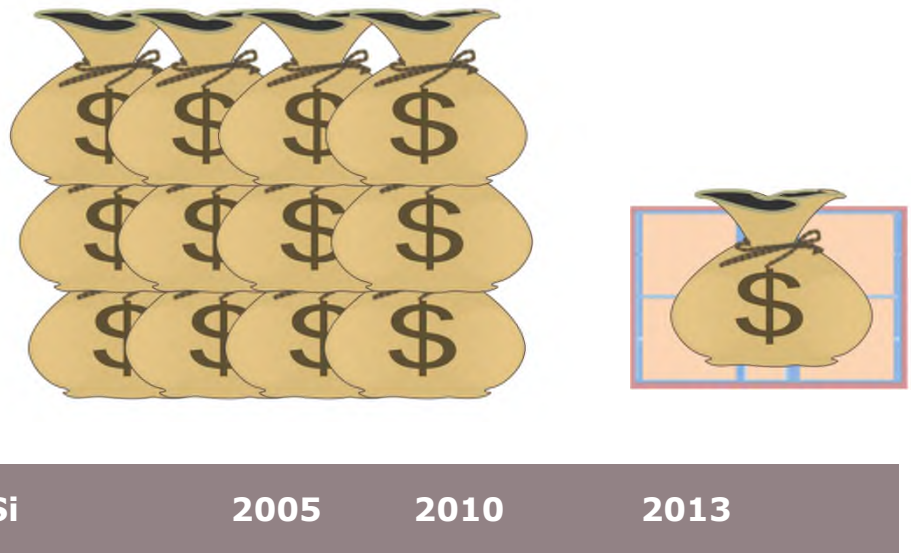
Larger range

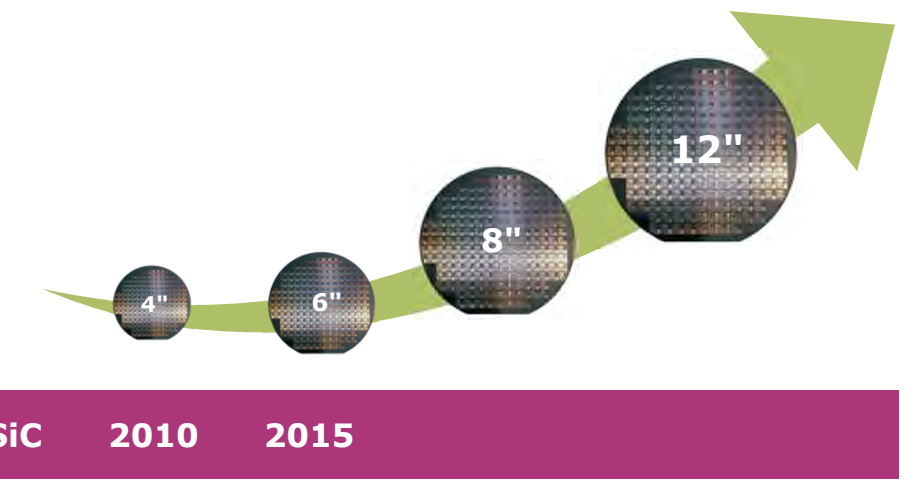


SiC addresses several concerns
Range and charge time improvements



Wide Band Gap could be a game changer
SiC is an expensive material





SiC is an expensive material, but

$ / Amp ratio is decreasing fast

- Higher demand -> lower cost
- Better Wafers -> lower defect density
- Wafer size increase -> lower cost

- **Manufacturing cost**
  - Higher Wafer cost
  - Higher defects density
  - Lower yields

Picture source: Internet

Efficiency improvements of SiC can save system costs at car level

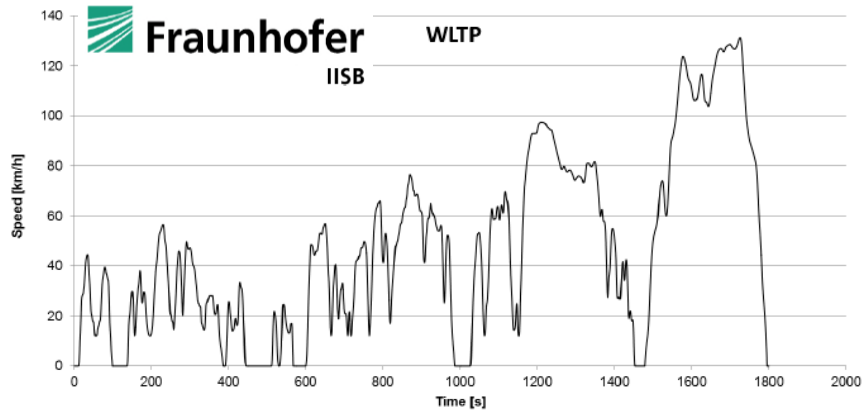
Drive cycle study shows

› A SiC inverter shows 2/3rd less losses.

Efficiency Improvement

› For a given autonomy, this leads to savings in the high voltage battery.

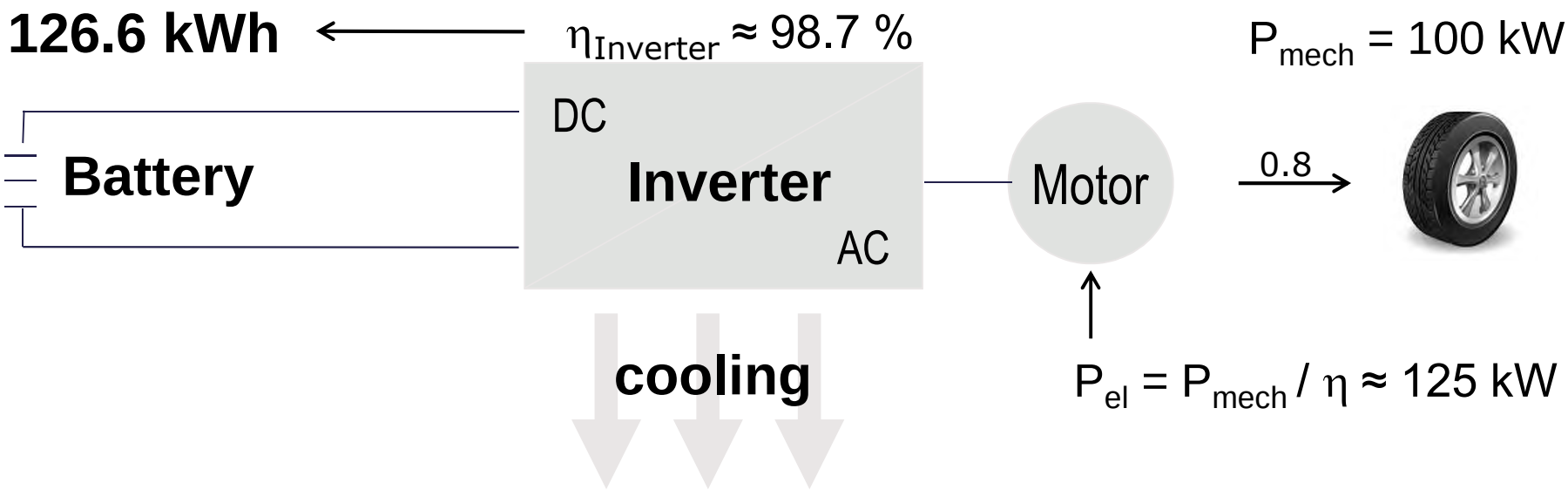
Battery size



Driving Cycle	Si based Inverter	**SiC** based Inverter
Artemis Urban	94.6%	98.1%
Artemis Road	97.2%	99.0%
Artemis Highway	98.2%	99.3%
NEDC	96.3%	98.7%
WLTP	96.8%	98.9%

Why is efficiency important?

Scenario:
Driving a vehicle with 100kW "at the wheel"



Even with a high efficiency the losses of an inverter are in the **kW** range

$\eta_{el} = 98.7\ \%$ for SiC -> $P_{losses} = 1.3\% * 126$ kW = 1.6 kW

Picture source: Internet

Efficiency improvement by SiC
Battery reduction by ~5% possible

Driving

Battery output		Inverter Efficiency		Motor Transmission Efficiency		@ Wheel
129.8 kWh		Si 0.963		0.8		100 kWh
126.6 kWh		SiC 0.987		0.8		100 kWh

Battery input						
38.5 kWh		Si 0.963		0.8		50 kWh
39.5 kWh		SiC 0.987		0.8		50 kWh

Recuperation

Effect of
2.4% better
Inverter Efficiency

~ 5% lower
Battery
Capacity

Driving Cycle	Si based Inverter	SiC based Inverter
NEDC	96.3%	98.7%

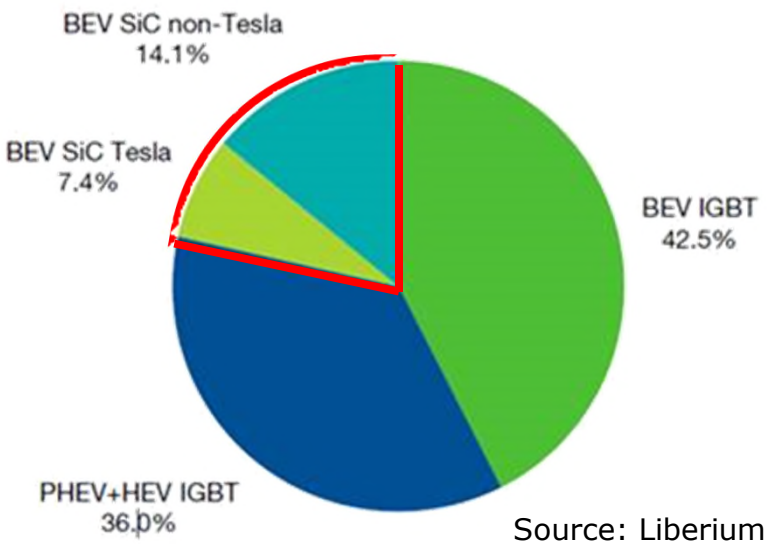
Battery Balance		Needed Battery Capacity
129.8 kWh – 38.5 kWh		Si 91.3 kWh
126.6 kWh – 39.5 kWh		SiC 87.2 kWh

Penetration of SiC into xEV market
High benefit for vehicles with large batteries

Efficiency Improvement

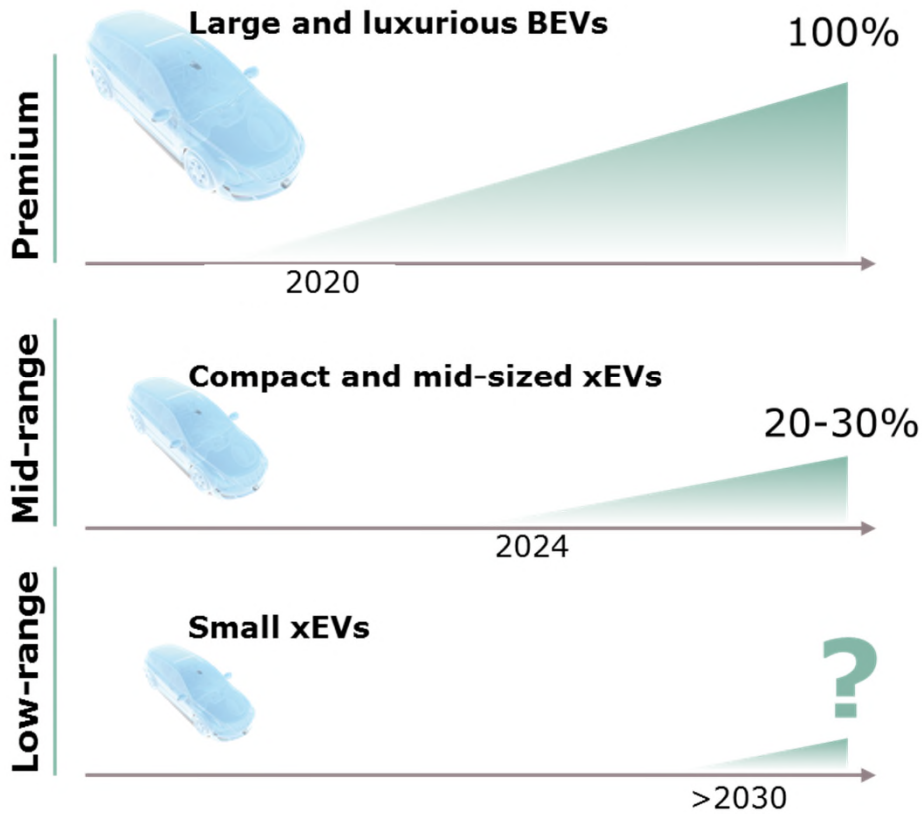
- A SiC inverter shows 2/3rd less losses.
- For a given autonomy, this leads to savings in the high voltage battery.

Estimated inverter share in 2025



Source: Liberium estimates

Highest benefit for high voltage systems and vehicles with large batteries expected



Agenda

1. Silicon Carbide at Infineon
2. Silicon Carbide in automotive
   - Challenges
   - The system benefits of SiC
3. Why is SiC now closer to Reality?
4. Next generation of power module

Recapitulation

- **Reliability** Challenge: Defect density and Gate Oxide Robustness
  - **Wafer quality** improving significantly
  - Infineon`s SiC MOSFET design based on **Trench Technology** and long time experience enables the **reduction of fit rates**

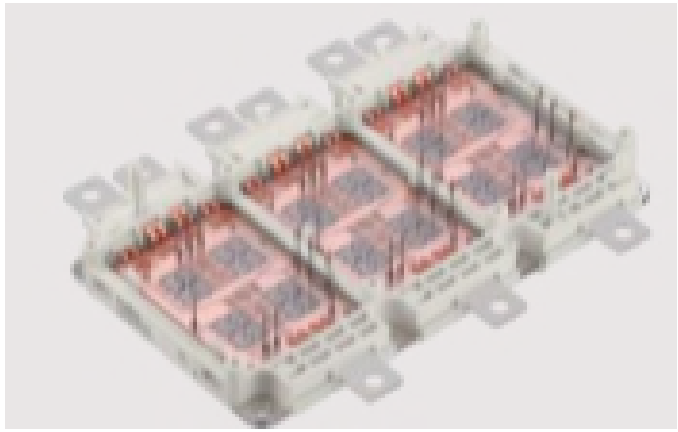
- **Cost** Challenge
  - High demand of SiC Wafers **lowers Wafer cost**
  - **Economy of scale:** 150 mm Wafer in SiC production line
  - **Lower defect density**
    - improves yield
    - enables larger die sizes

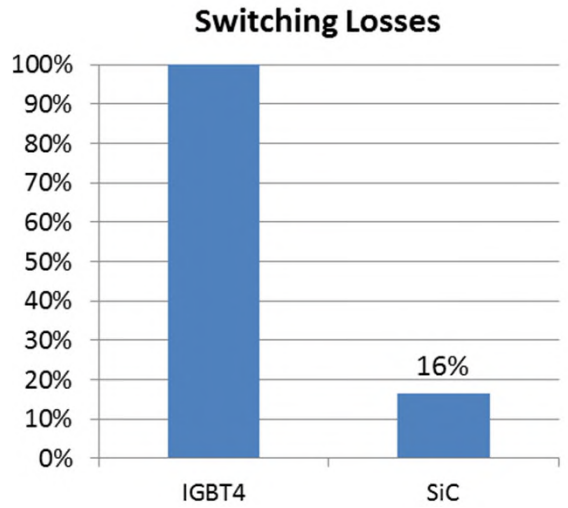
Agenda

1. Silicon Carbide at Infineon
2. Silicon Carbide in automotive
   - Challenges
   - The system benefits of SiC
3. Why is SiC now closer to Reality?
4. Next generation of power module

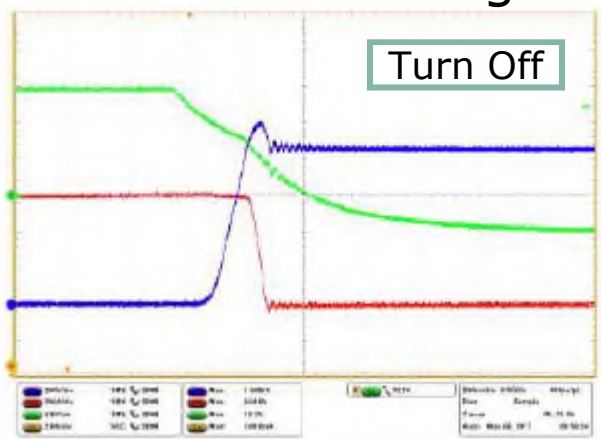
Inverter Module
HybridPACK™ Drive with CoolSiC™

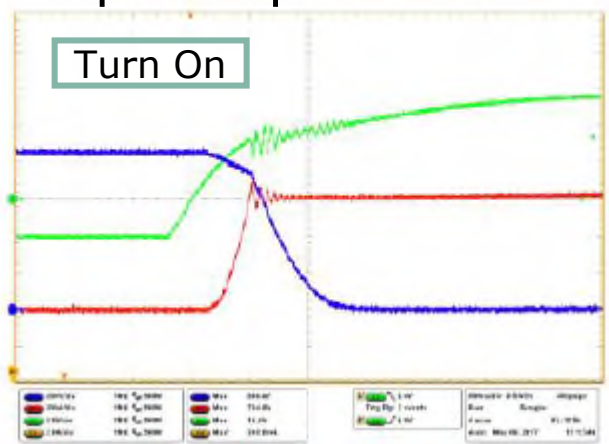
› Comparison of 1200V SiC and Si (IGBT4)

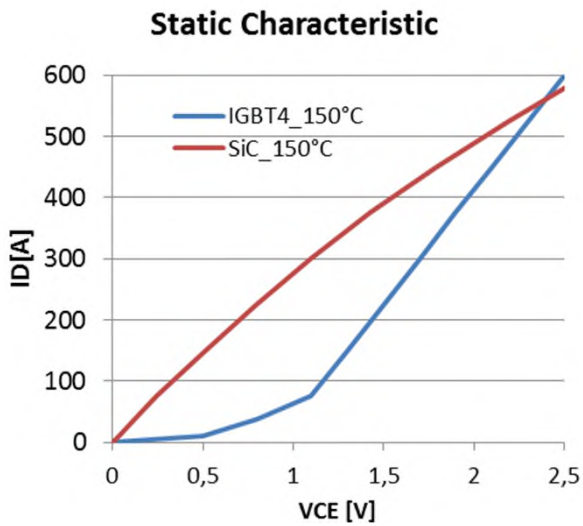




Smooth switching for drop in replacement

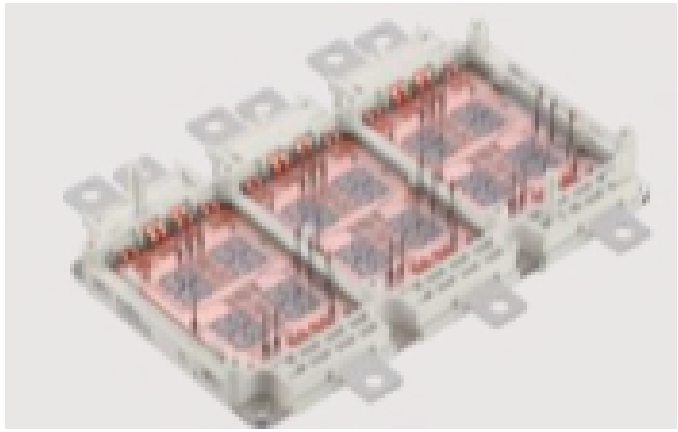


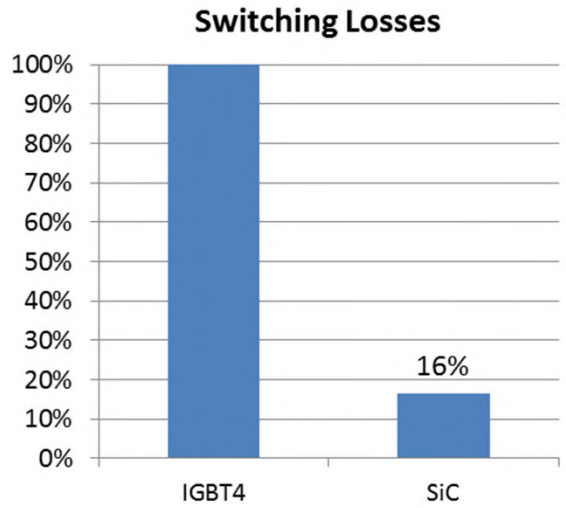


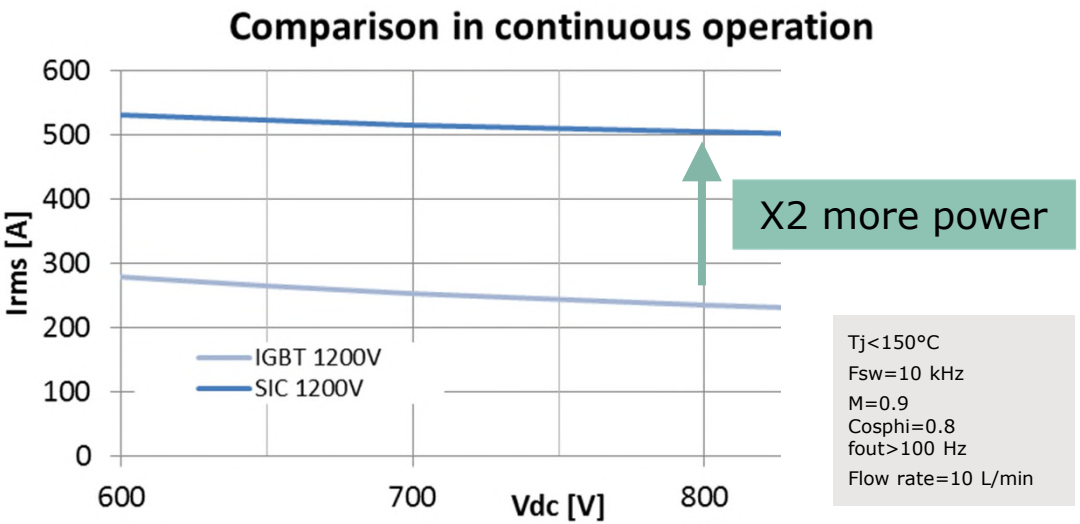


Inverter Module
HybridPACK™ Drive with CoolSiC™

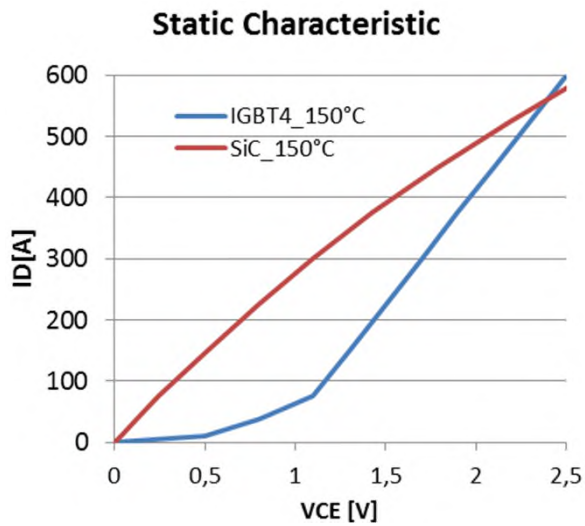
› Comparison of 1200V SiC and Si (IGBT4)



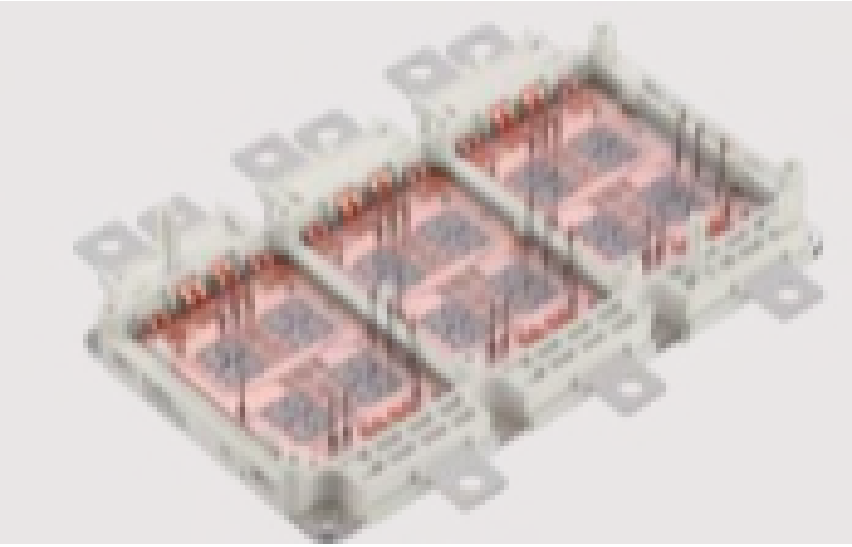




Tj<150°C
Fsw=10 kHz
M=0.9
Cosphi=0.8
fout>100 Hz
Flow rate=10 L/min



HybridPACK™ Drive with CoolSiC™
SiC doubles power density



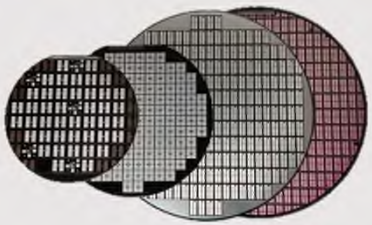
300kW (500A - 800V) SiC inverter module

Drop in replacement to Si modules

Power density almost doubled

Infineon has unparalleled package expertise to match OEM and Tier-1 needs

Bare die



Si bare dies

SiC bare dies

Discretes

Si IGBT

SiC MOSFET

Scalable products

HybridPACK™ Double-Sided Cooling

Plug-n-Play

HybridPACK™ solutions

Easy modules

SiC optimized package solution

Silicon Carbide (SiC) Semiconductors for xEV are getting closer to Reality

› Increasing robustness - Reducing fit rates

› Shorter charge time at 800V battery (~50%)

› Increased battery range (~5 - 10%)

› Reduced system/battery costs (~$500 - $1000)

10M BEVs in 2025

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