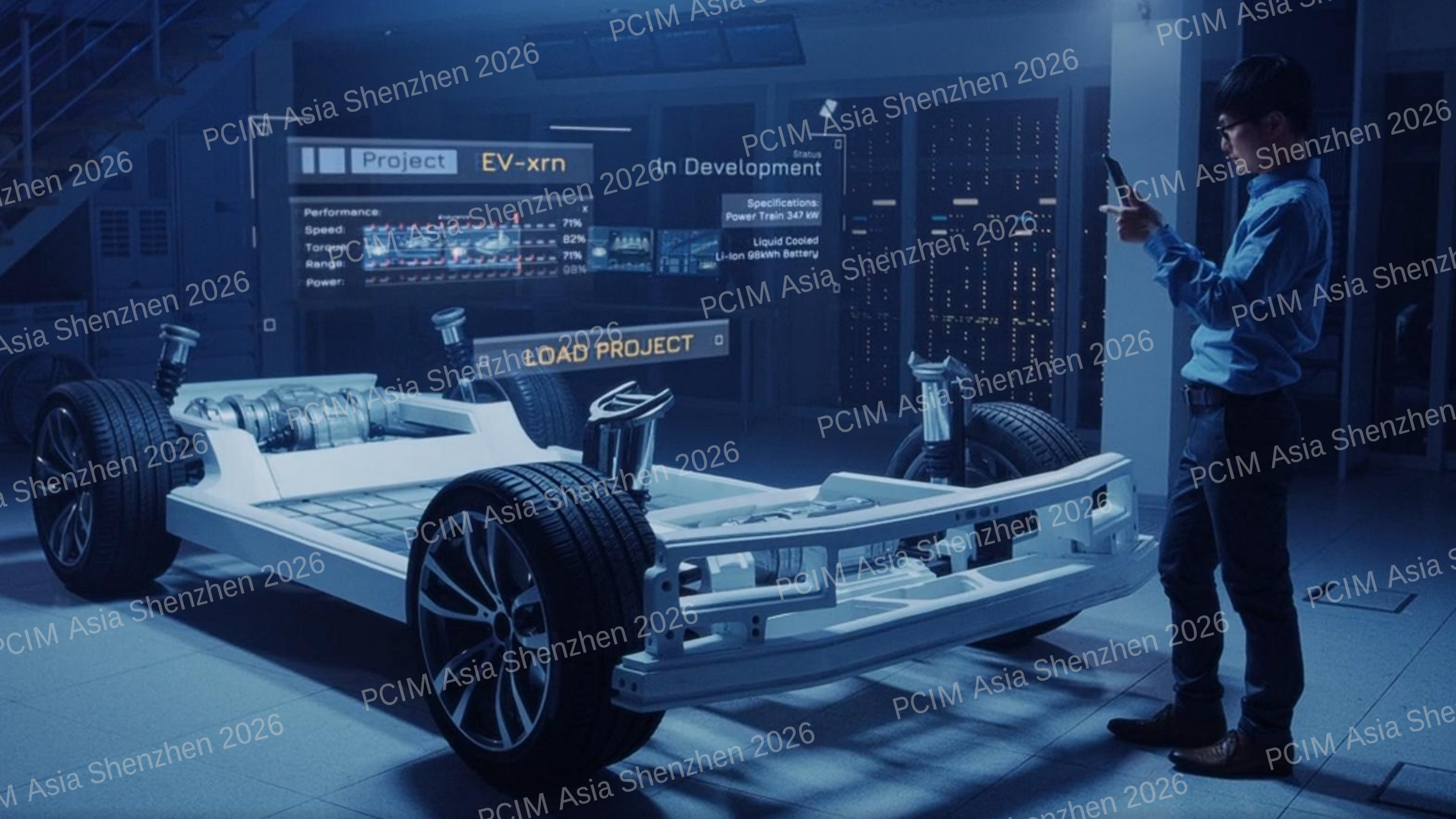


Semiconductor Contribution to Performance & Efficiency of Automotive Traction Inverters

Mark Nils Muenzer, Fellow Motor Control Solutions



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Semiconductor contribution to Performance & Efficiency of Automotive Traction Inverters



1 Performance & Efficiency of EV Powertrains

3

2 Power Semiconductor Technologies for Automotive Traction Inverters

4

3 Loss reduction by Slew Rate Control and Dead Time Optimization

5

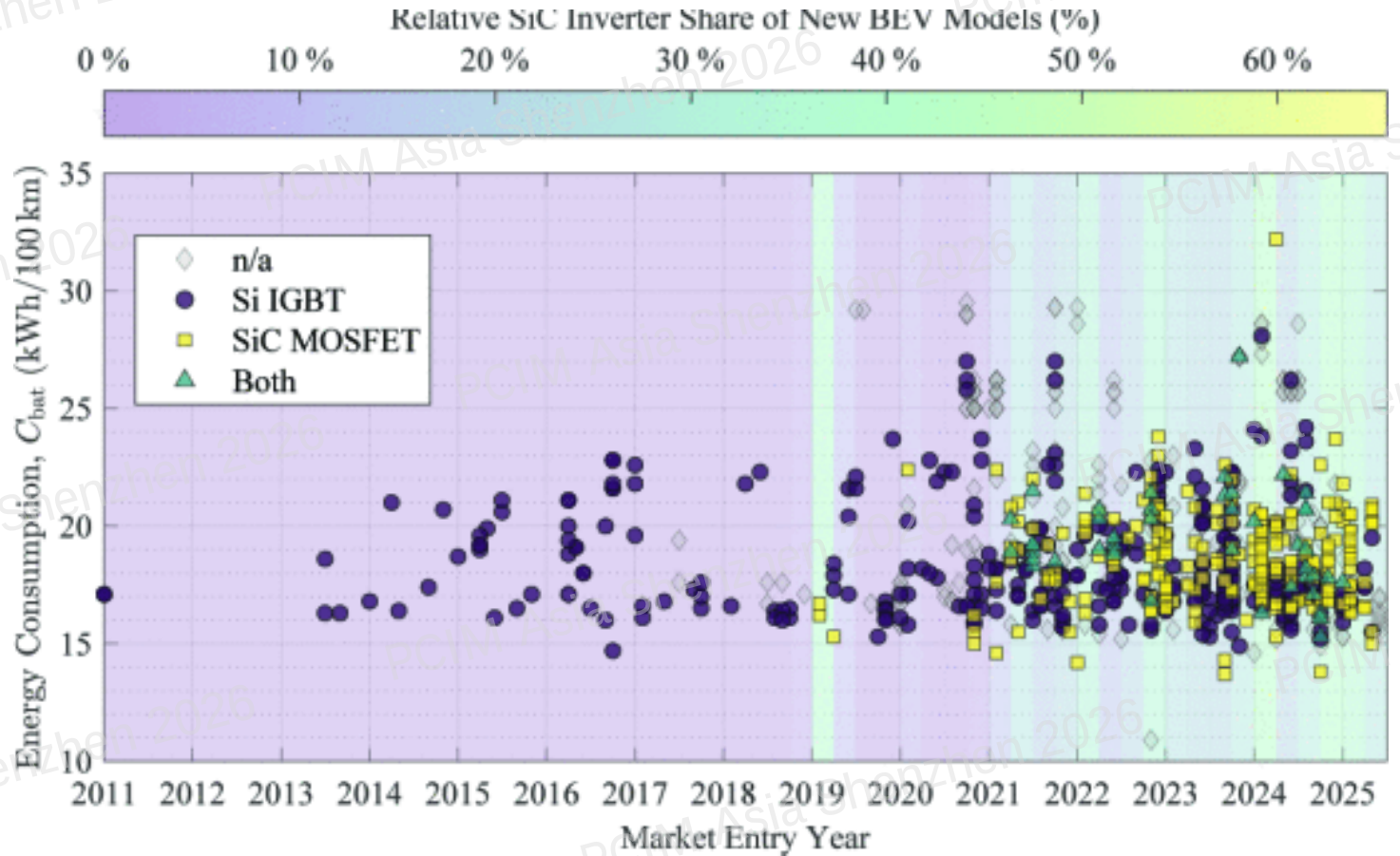
4 Next generation EV Powertrains

6

Energy consumption on vehicle level remains high despite significant improvements in powertrain efficiency



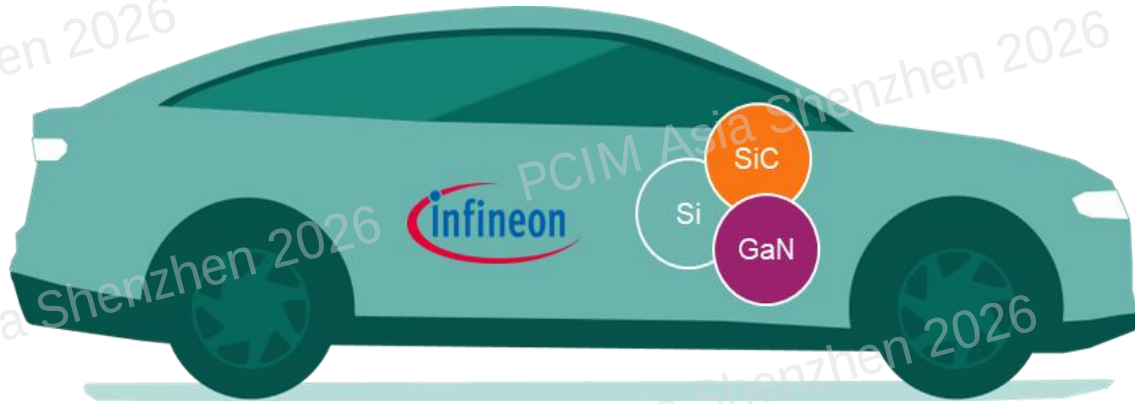
Energy consumption statistic by market entry date



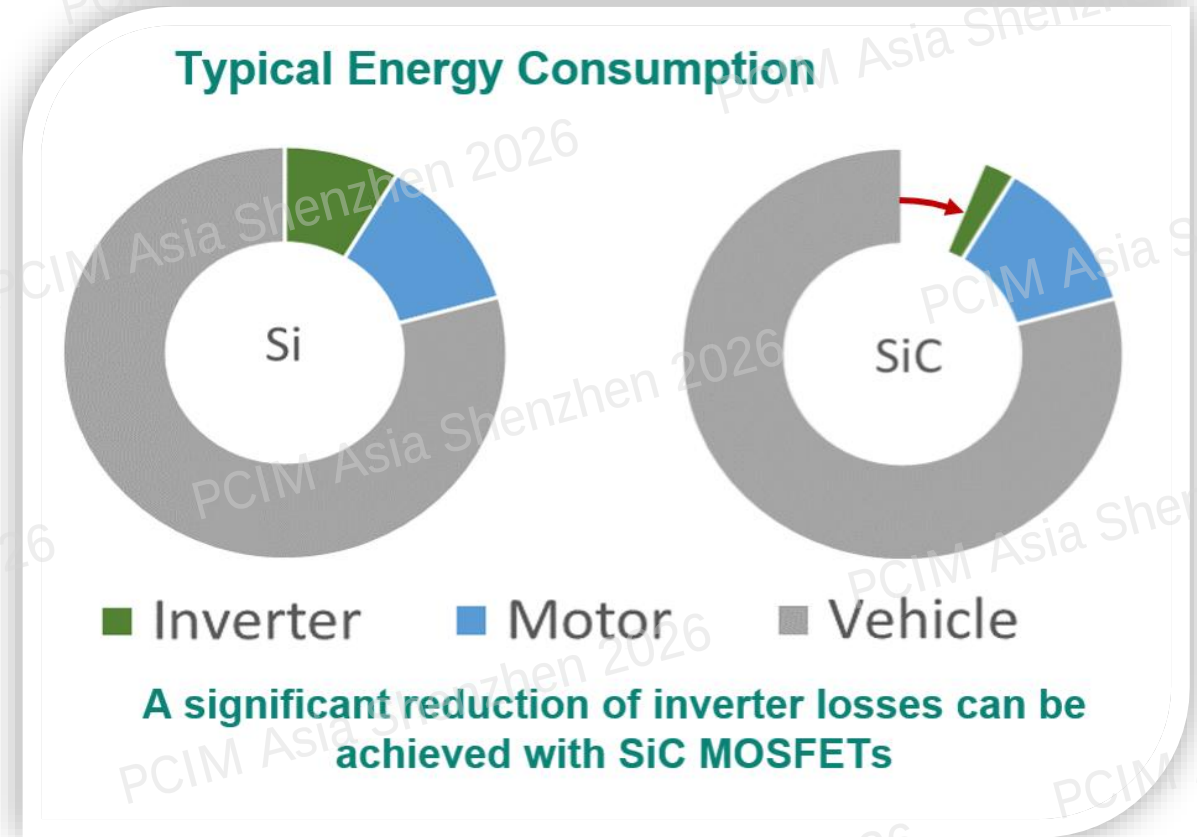
C. Sachs and M. Neuburger, "A Data-Based Review of Battery Electric Vehicle and Traction Inverter Trends," *IECON 2025 – 51st Annual Conference of the IEEE Industrial Electronics Society*, Madrid, Spain, 2025, pp. 1-8, doi: 10.1109/IECON58223.2025.11221818

Energy demand is defined by vehicle design & drive cycle

Good powertrain design provides efficient energy conversion



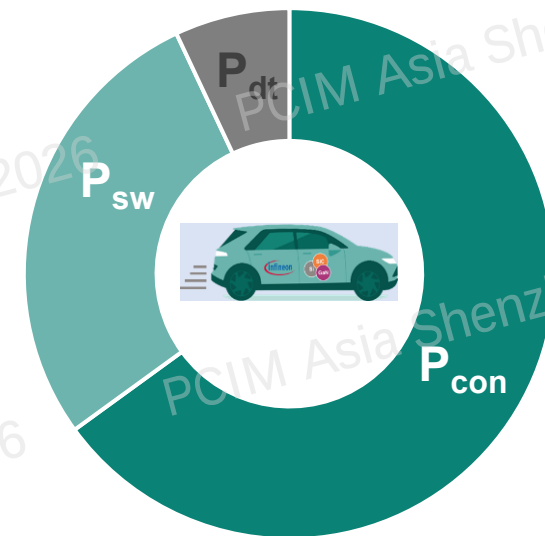
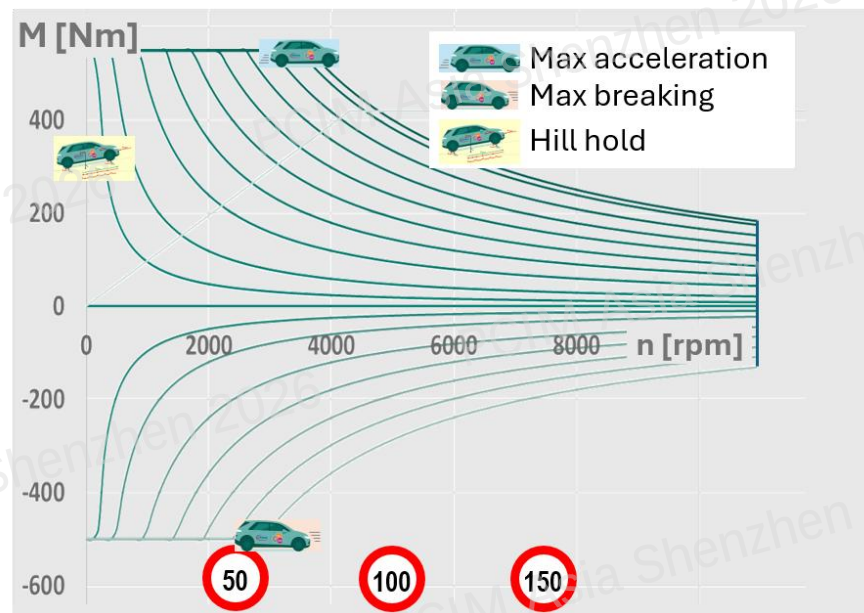
Name	Value	Unit
Car mass	2100	kg
Front surface area	2.34	m ²
Drag coefficient	0.24	
Tire-road friction coefficient	0.015	
Inverter to wheel efficiency	90	%



Drive Cycle	Distance [km]	Ø Speed [km/h]	max Speed [km/h]	Sedan [kWh/100km]
CLTC	14,48	28,96	114	14,3



Semiconductor contribution to peak power



Peak power demand

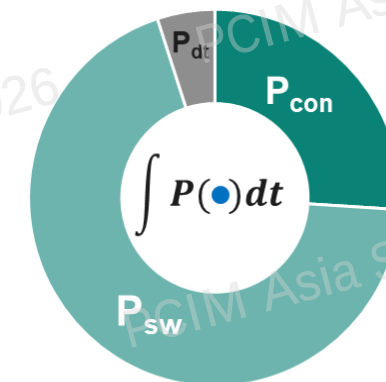
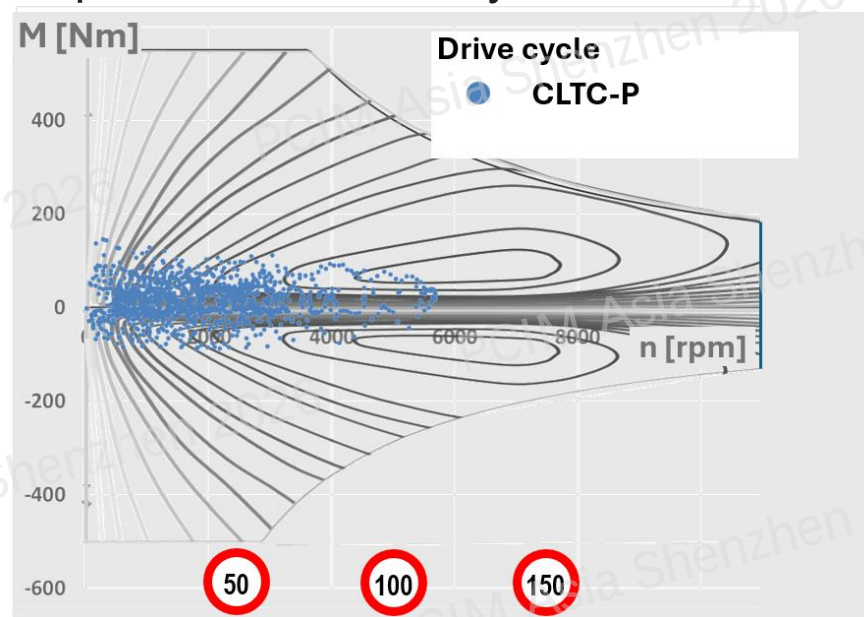
defines powertrain cost.

Power semiconductor performance is highly dependent on lowest conduction losses.

Traction inverter development targets cost efficient peak power and drive cycle optimized powertrain efficiency



Semiconductor contribution to powertrain efficiency



Peak power demand

defines battery and energy cost.

Power semiconductor performance is highly dependent on lowest switching losses.

Semiconductor contribution to Performance & Efficiency of Automotive Traction Inverters



1

Performance & Efficiency of EV Powertrains

3

2

Power Semiconductor Technologies for Automotive Traction Inverters

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3

Loss reduction by Slew Rate Control and Dead Time Optimization

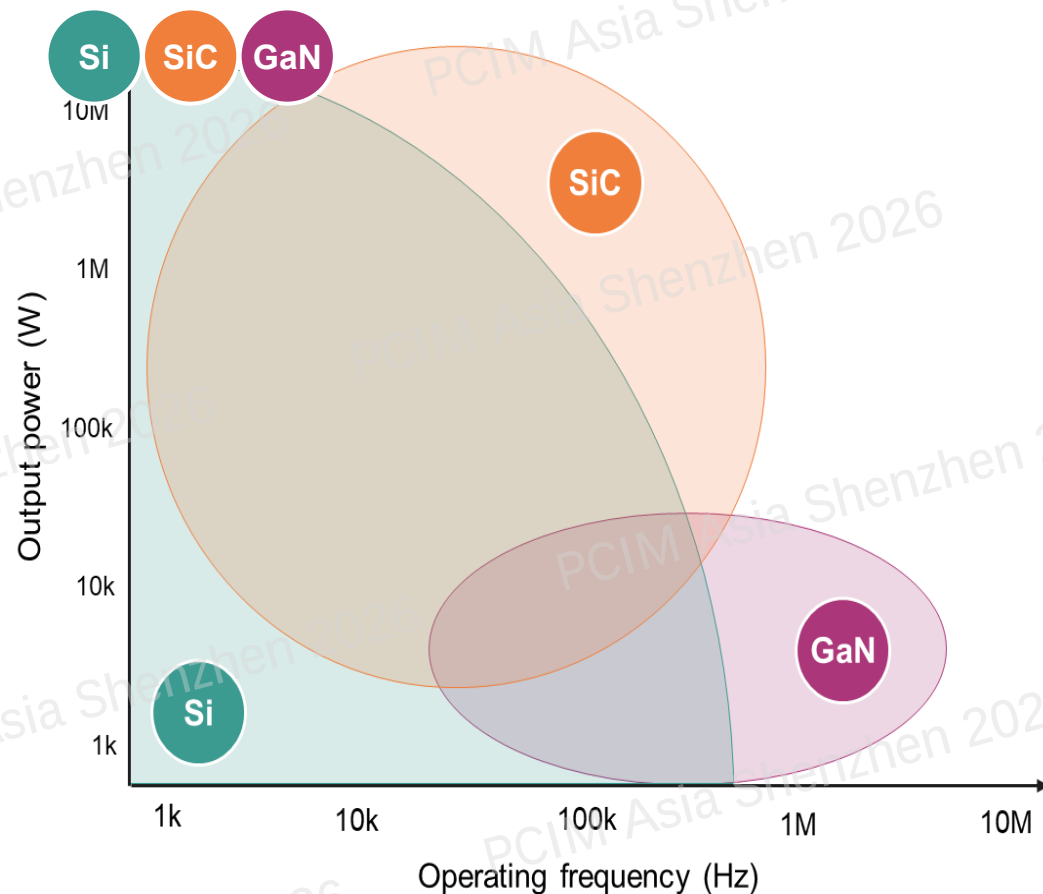
5

4

Next generation EV Powertrains

6

Power technologies – key characteristics comparison at device level



Max temperature: SiC supports higher temperatures (T_j up to 200°C Vs 150°C-175°C for GaN) and has a lower R_{DS_ON} increase over temperature ($\times 1.65$ Vs $\times 2.0$ for GaN; 25/150°C).



Max voltage: SiC scales very efficiently up to 1200V, where GaN is more limited by its lateral construction. 1200V vertical GaN possible but with impact on cost & performance.



Switching loss: GaN switching loss advantage for traction inverter is limited by system level boundary conditions.



Integration: with its Si substrate, lowest Q_g and lateral construction, GaN offers unique integration capabilities (monolithic iGaN or bi-directional switch)



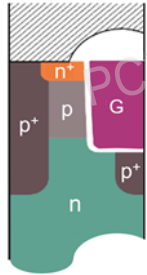
Device cost* \$·A⁻¹: for most traction inverter applications, ($R_{DS_ON} < 10\text{m}\Omega$, $T_j > 175^\circ\text{C}$), Si still offers the best position. GaN higher than SiC but w potential to catch-up

Source: Infineon

* Comparison for 650V devices, based on internal costs

Trench structure has proven to combine competitive performance with market leading quality and reliability

TRENCH SiC MOSFET



Power density
(Shrink Potential)



Ease of use



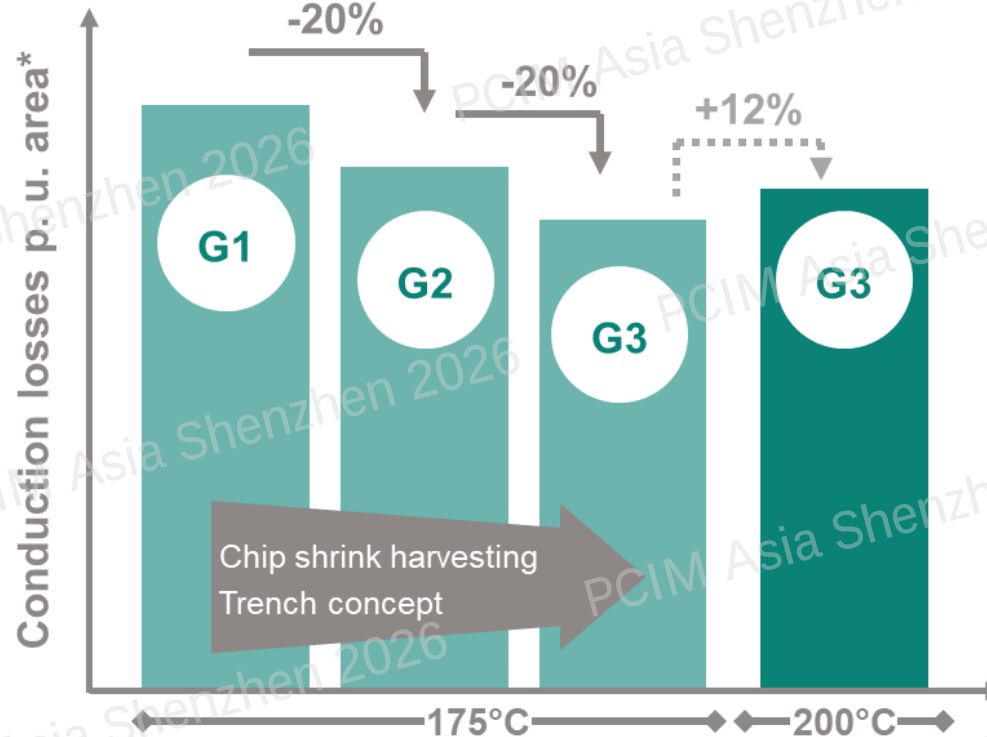
Robustness



Reliability

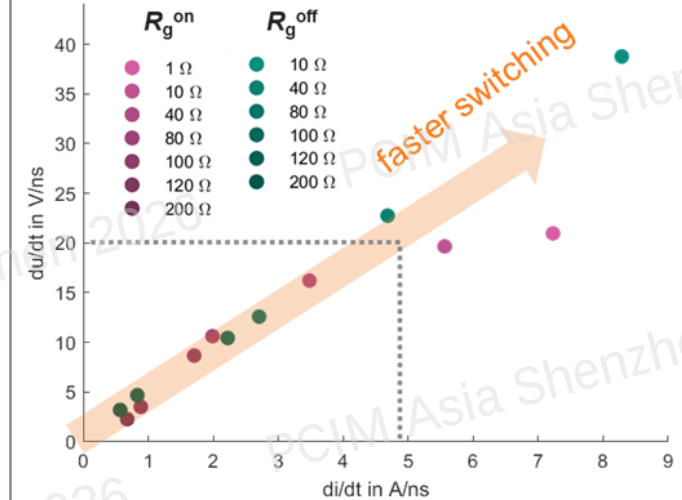


Manufacturing
Complexity



*1200V SiC MOSFET, @ high T_j , full-load operation
Actual conduction loss improvement depending on application conditions

Gate resistance influence



Switching speed



Dead time

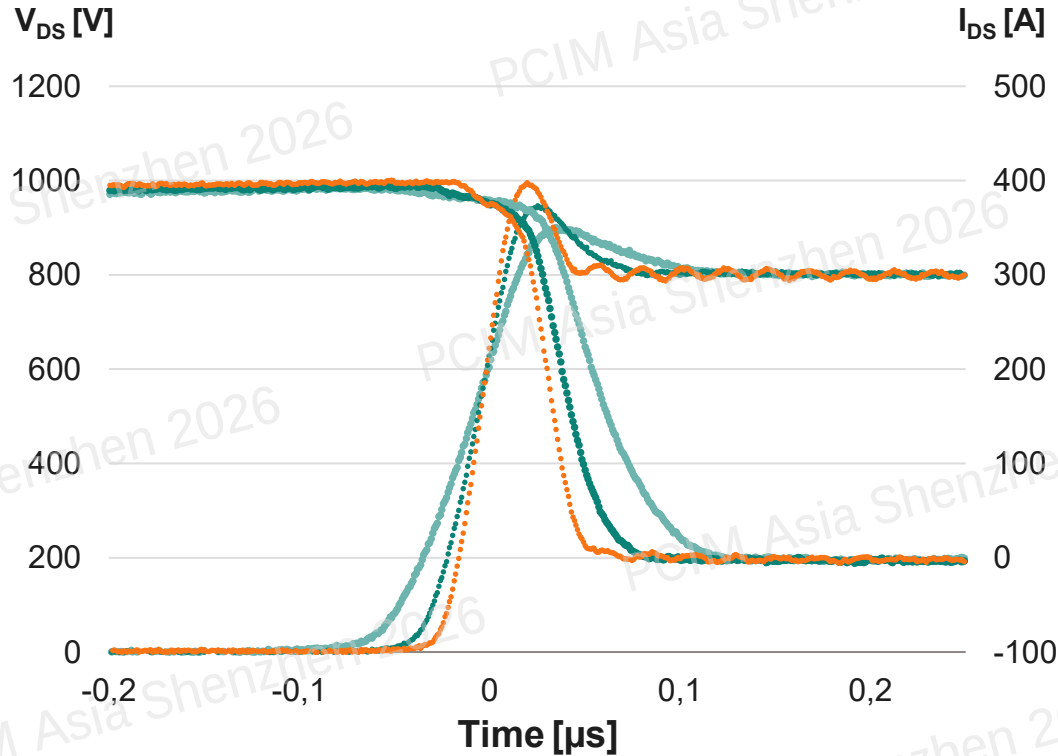


EMC



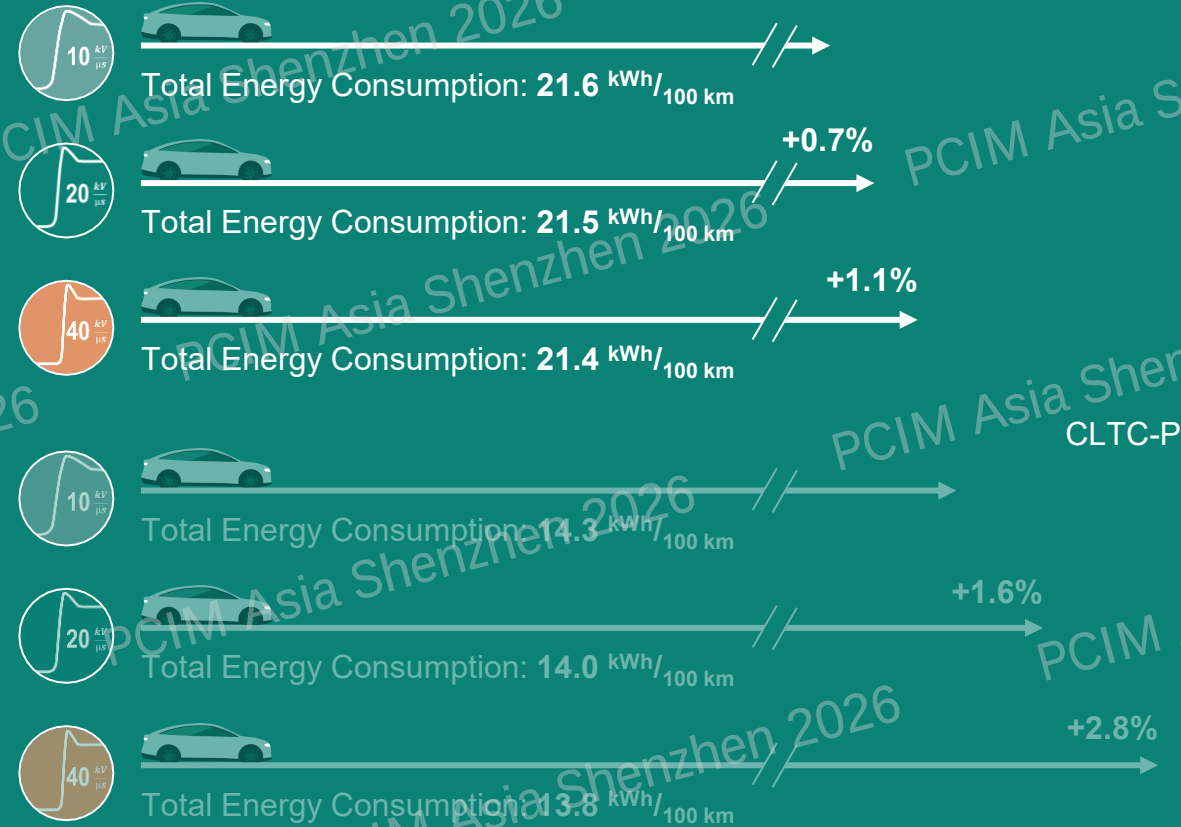
SiC MOSFETs support increased switching speed Vehicle range improvements are connected to steeper slopes

Turn-off waveforms



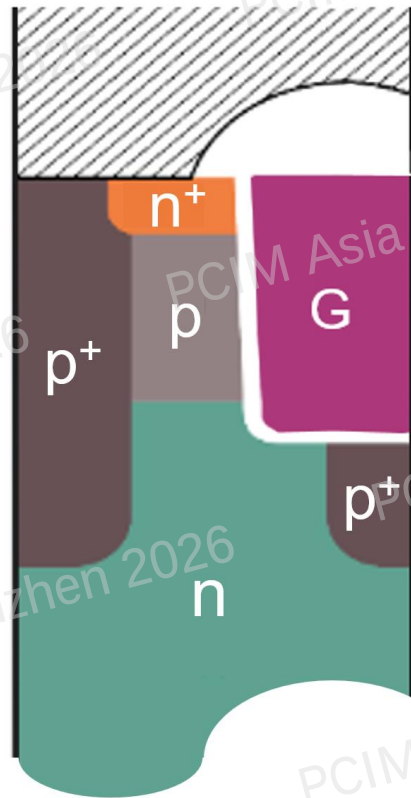
$V_{bus} = 800$ V, $V_{GS} = -5$ V/18 V, $I_D = 360$ A
 $T_{vj} = 175^\circ$ C, $L_{loop} \sim 25$ nH

Artemis Highway



Superjunction concept tackles resistance in drift region as main contributor to conduction loss in 1200V SiC MOSFETs

Conventional asymmetric trench-gate SiC MOSFET



At $T_{\text{junction}} 175^{\circ}\text{C}$

$R_{\text{cell-head}} \approx 1/3$

- Trench gate structure minimizes R_{ch}

$R_{\text{drift}} \approx 2/3$

- Dominates $R_{\text{DS(on)}}$
- Room for substantial improvement
- Next technological challenge

Asymmetric trench-gate SiC superjunction MOSFET (TSJ)



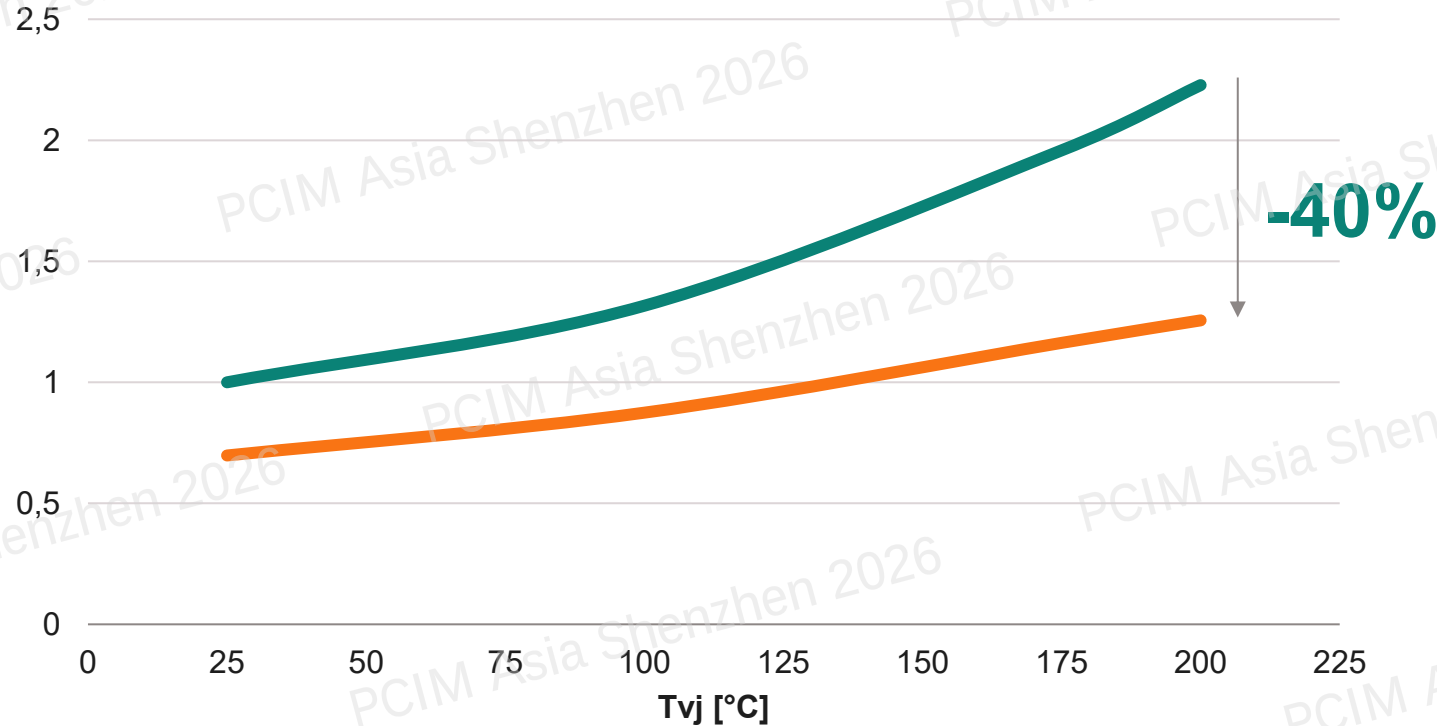
R_{drift} reduced through superjunction concept

Static characterization confirmed drastic reduction of specific $R_{DS(on)}$ and weaker temperature dependency

Normalized specific $R_{DS(on)}$ vs. temperature

$V_{gs} = 18\text{ V}$, nominal current

Normalized $R_{on} \times A_{act}$



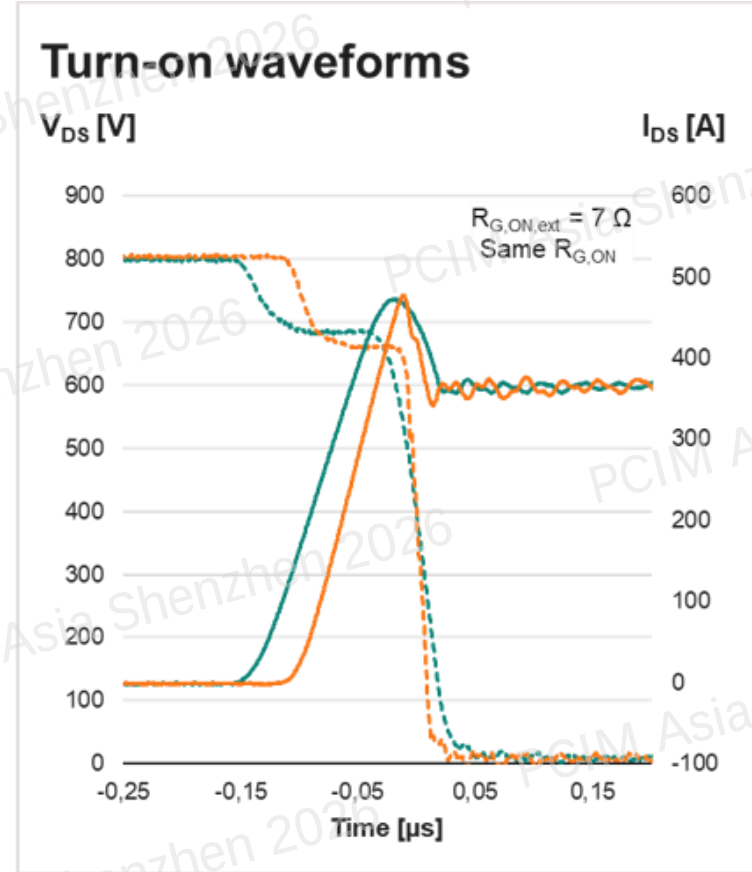
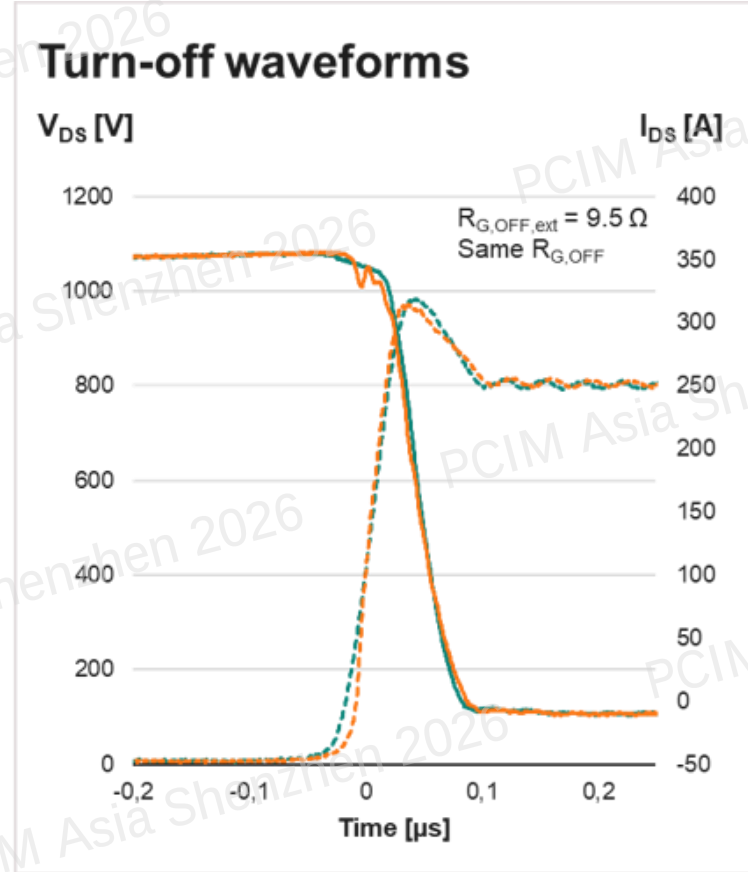
SiC
Gen2



SiC
TSJ



SiC SJ MOSFETs dynamic switching on real hard-ware shows clean waveforms, faster switching and good controllability



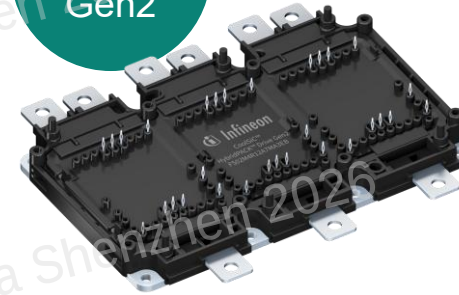
$V_{bus} = 800 \text{ V}$, $V_{GS} = -5 \text{ V}/18 \text{ V}$, $I_D = 360 \text{ A}$, $T_{vj} = 175^\circ\text{C}$, $L_{loop} \sim 25 \text{ nH}$

DUTs with same chip size

SiC Trench MOSFET

SiC Trench Super Junction MOSFET

SiC
Gen2



Clean

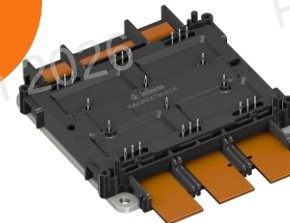


Fast

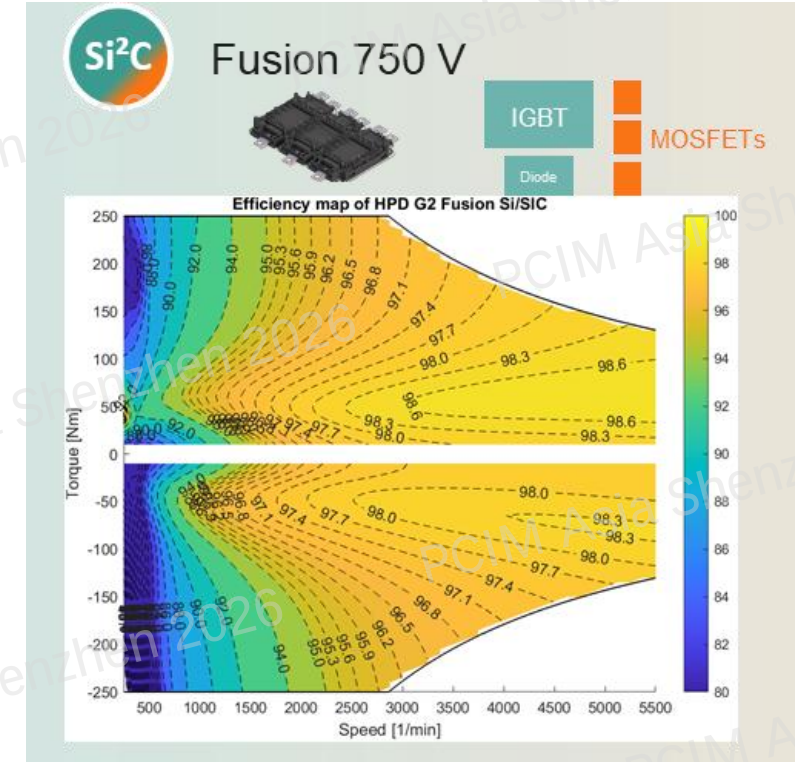
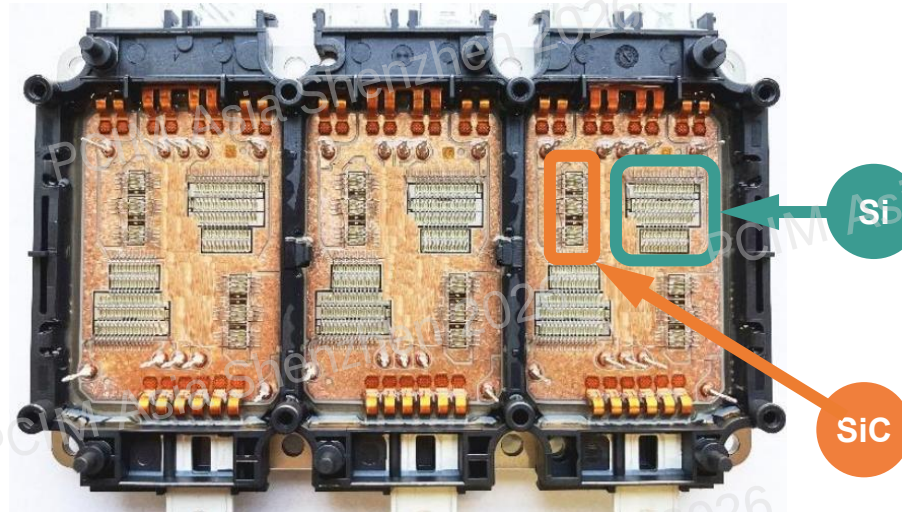
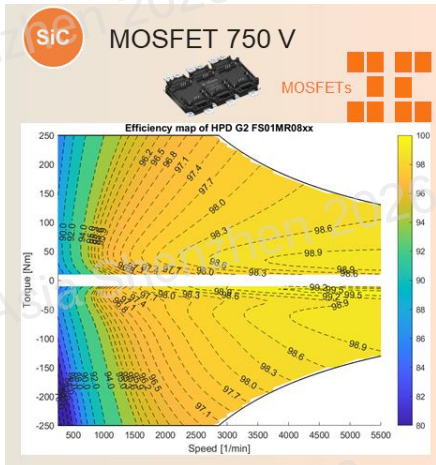
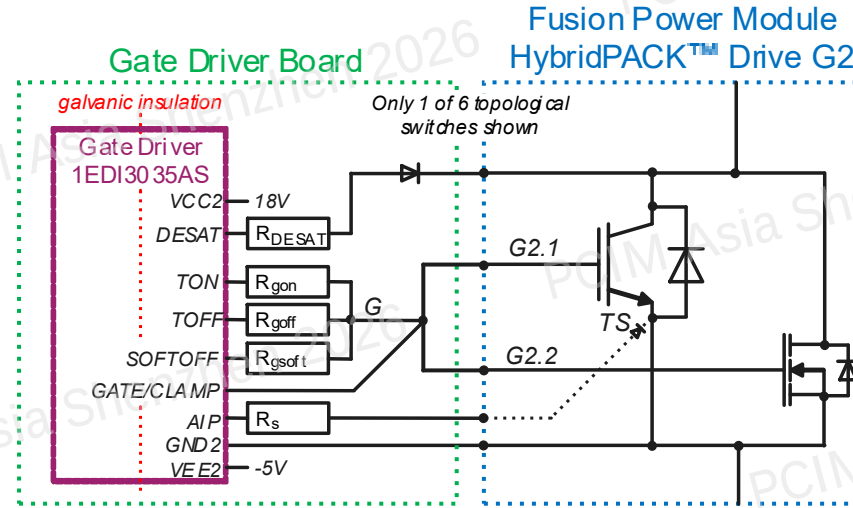
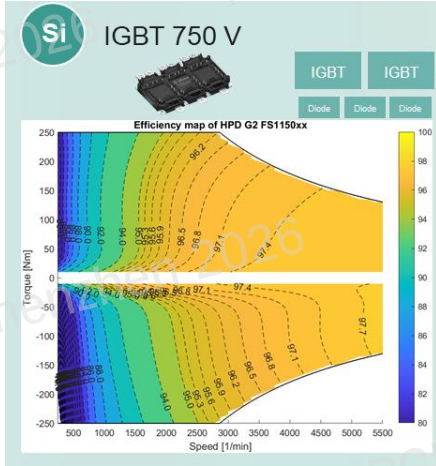


Efficient

SiC
TSJ



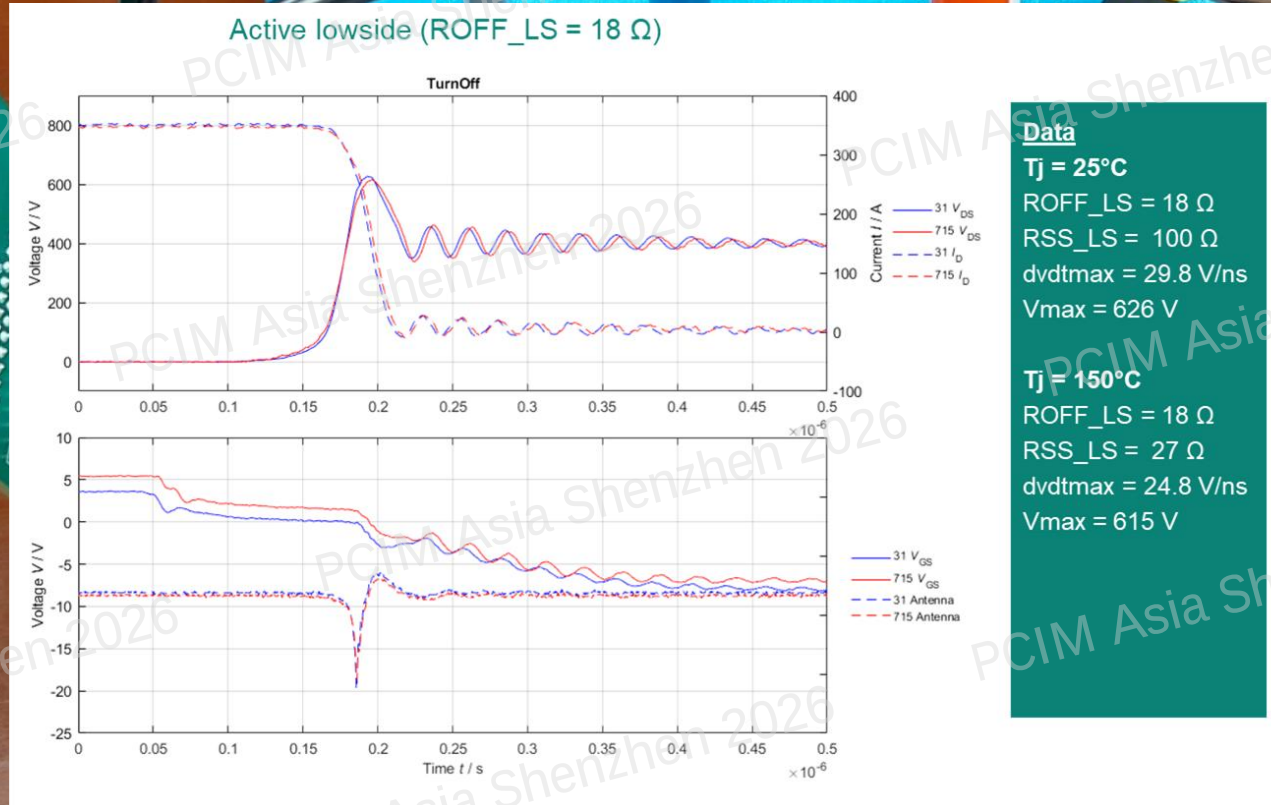
Fusion switch is a concept combining partial load efficiency with cost efficient peak power



Fusion switch

- addresses „Cost/Performance Dilemma“
- uses a simple „Single Gate Drive“
- offers extremely fast & smooth switching

Device characteristics make GaN HEMT a promising candidate for future traction inverters.



GaN HEMT prototype successfully tested up to 350A/350V

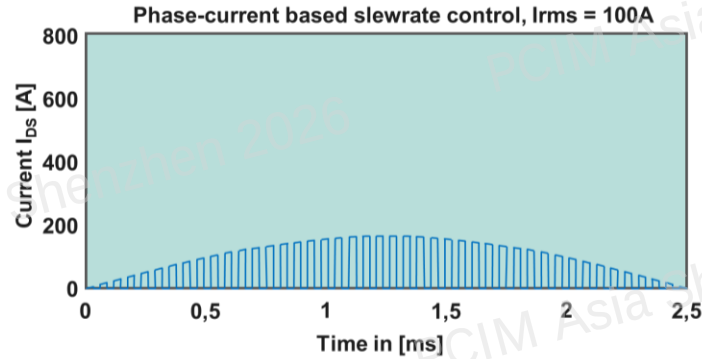
Semiconductor contribution to Performance & Efficiency of Automotive Traction Inverters



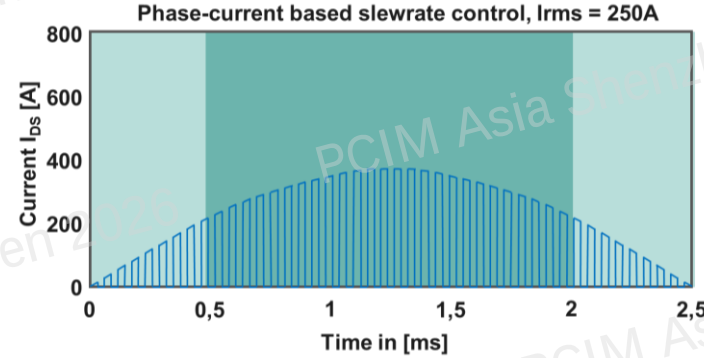
1	Performance & Efficiency of EV Powertrains	3
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Advanced gate control schemes like slew rate control offer performance gains by adapting switching speed

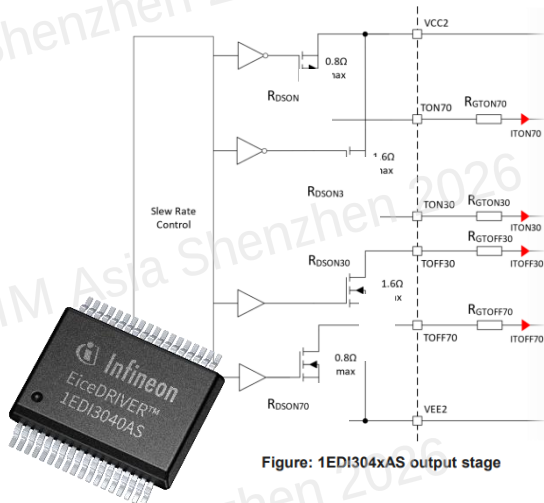
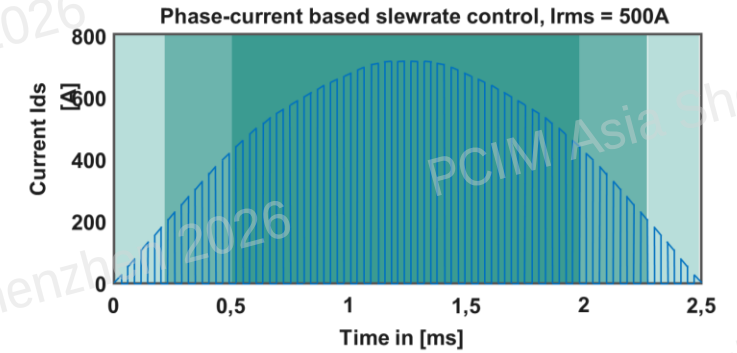
Low currents (<100 A)



Medium currents (100–300 A)



High currents (> 300 A)



Very fast switching:

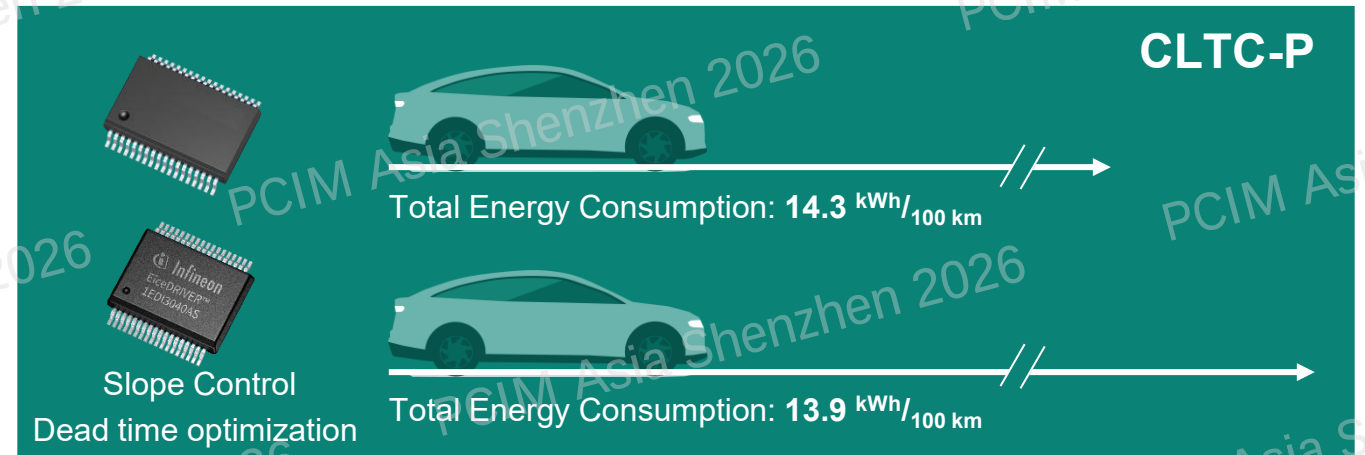
$$R_{GTON70} \parallel R_{GTON30}$$

Fast switching:

$$R_{GTON70}$$

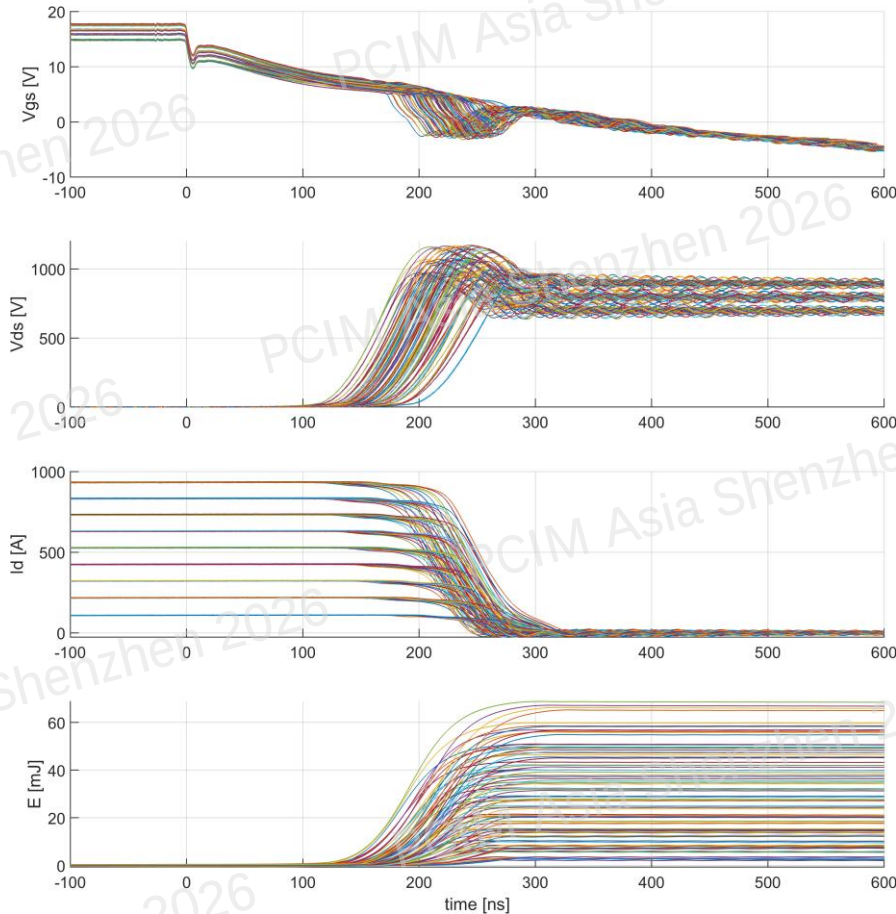
Normal switching:

$$R_{GTON30}$$

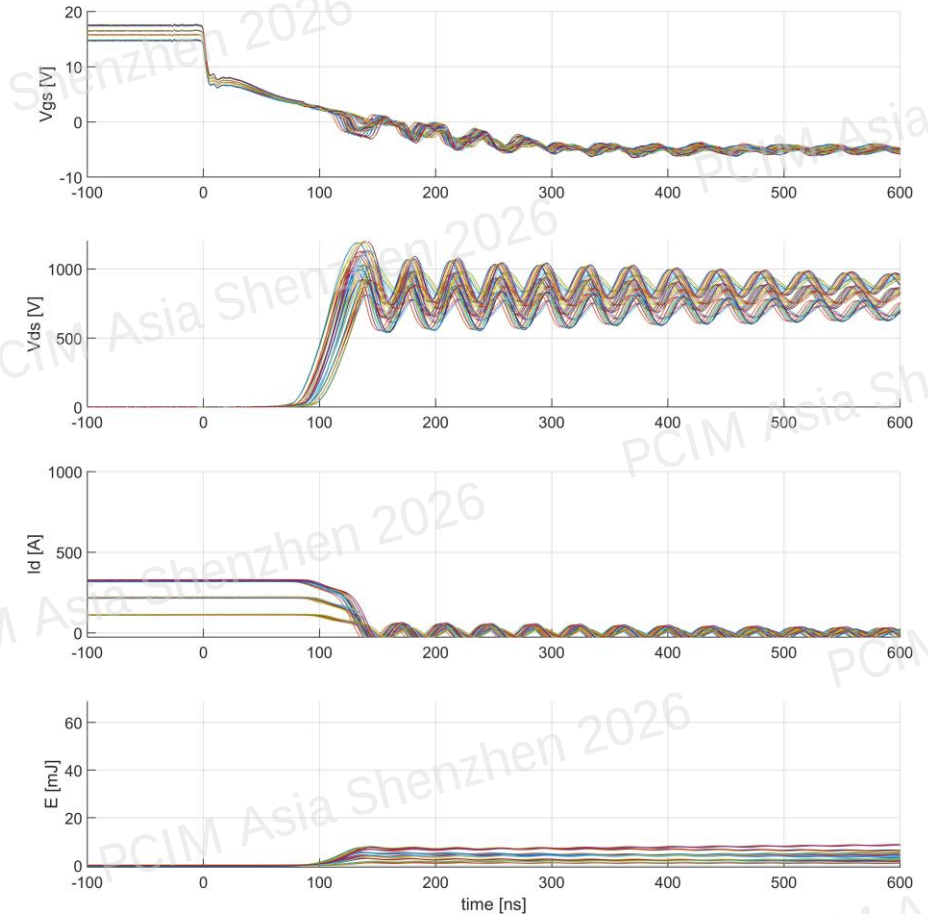


Switching waveforms confirm performance gains of adaptive slope control

Slow switching: Driver circuit designed to fulfill overvoltage limits under full load



Fast switching: Driver circuit optimized to fulfill overvoltage limits under partial load

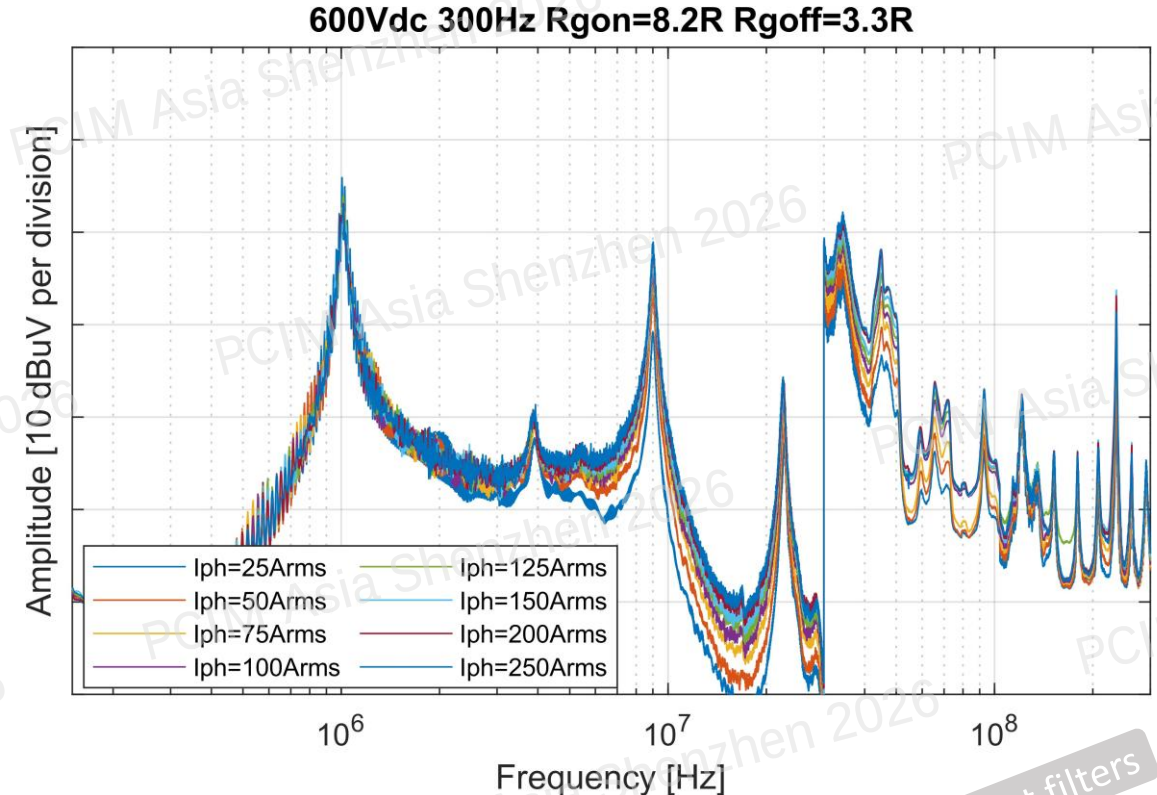


EMI test set up confirms that conducted emission increases with output current

EMI test setup without EMI filter for relative comparison of conducted emission



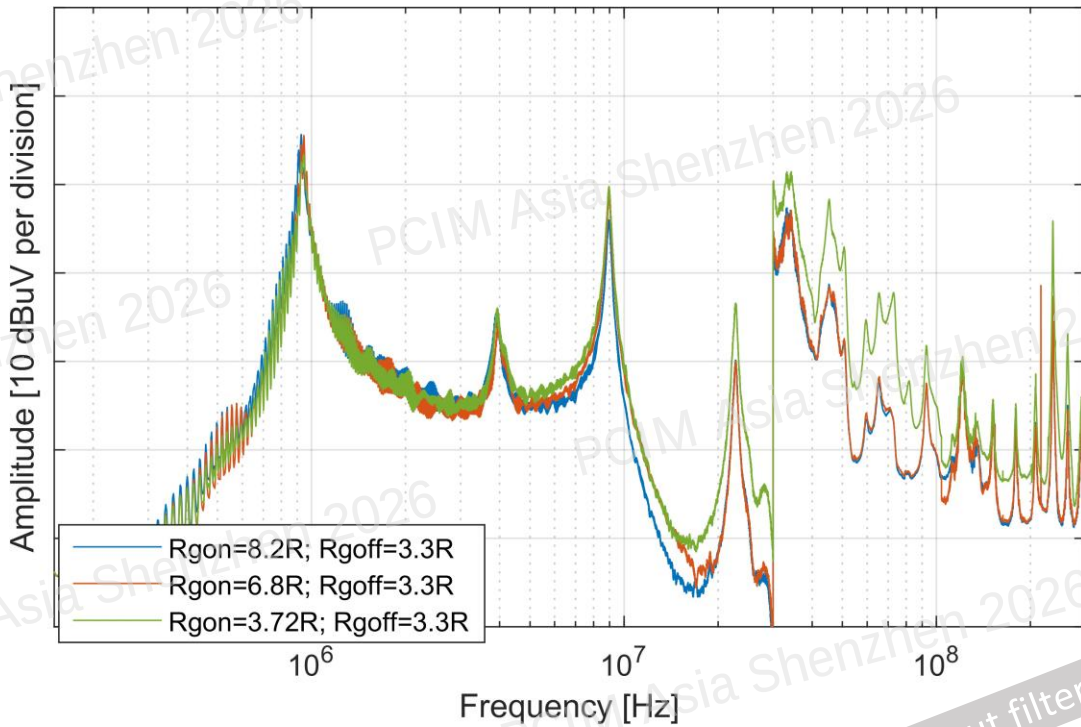
Influence of **phase current** on conducted emission (Vdc=600V, slow switching, fsw=10kHz)



without filters

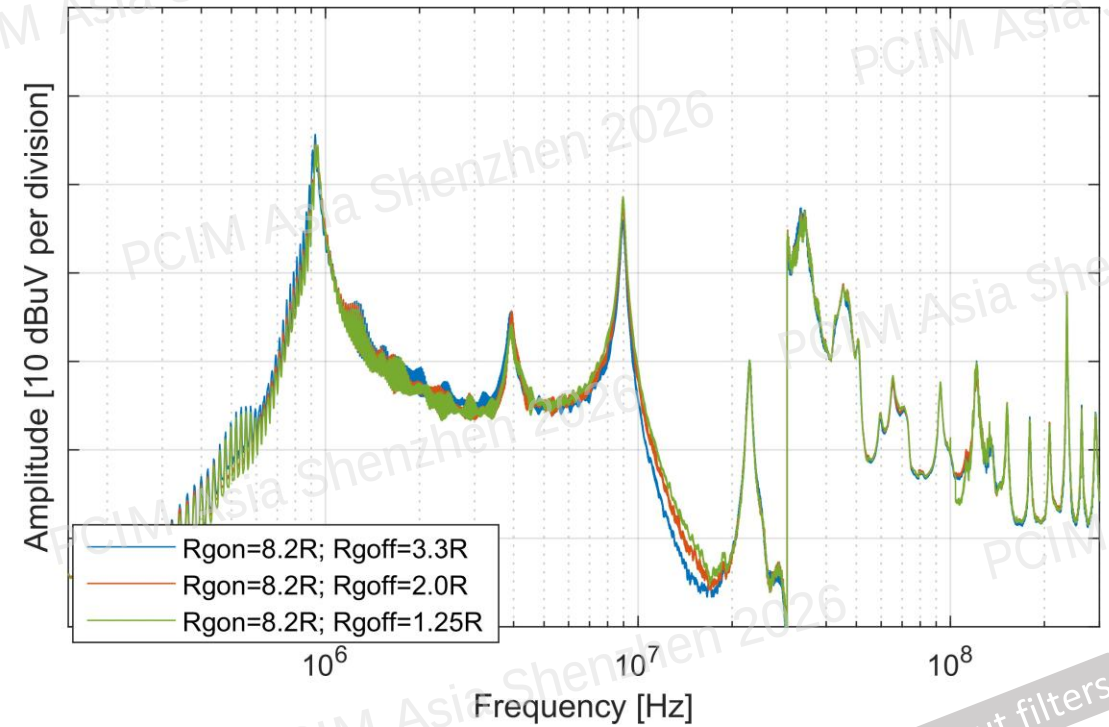
While a decrease in turn-on gate resistance increases EMI spectrum, turn-off gate resistance shows minor influence

Influence of **turn-on** gate resistance on conducted emission ($V_{dc}=600V$, $I_{ph}=50A$, $f_{sw}=10kHz$)



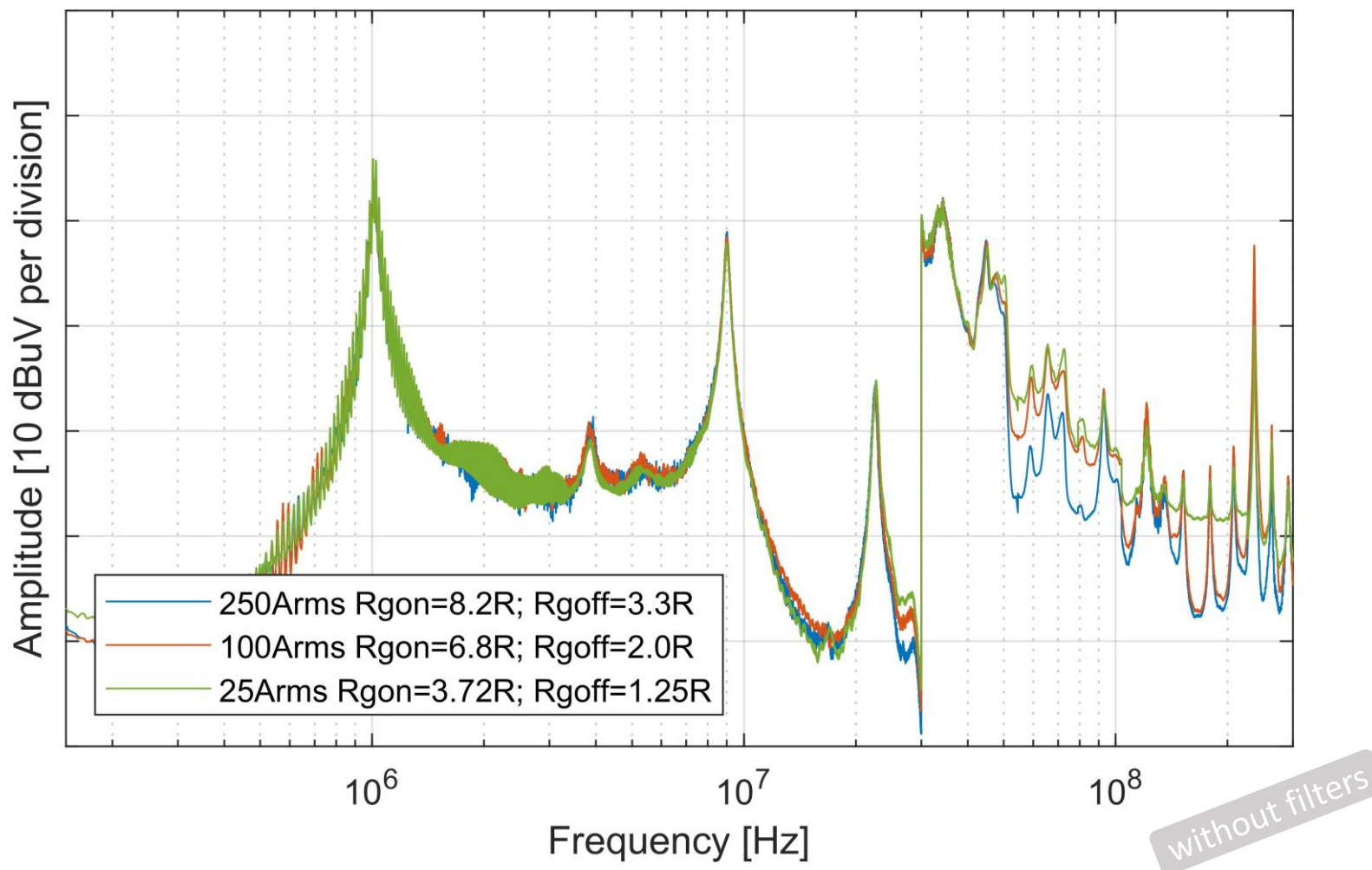
without filters

Influence of **turn-off** gate resistance on conducted emission ($V_{dc}=600V$, $I_{ph}=50A$, $f_{sw}=10kHz$)

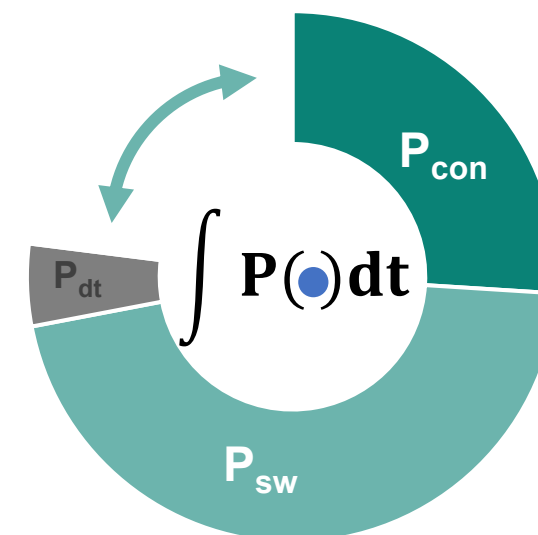


without filters

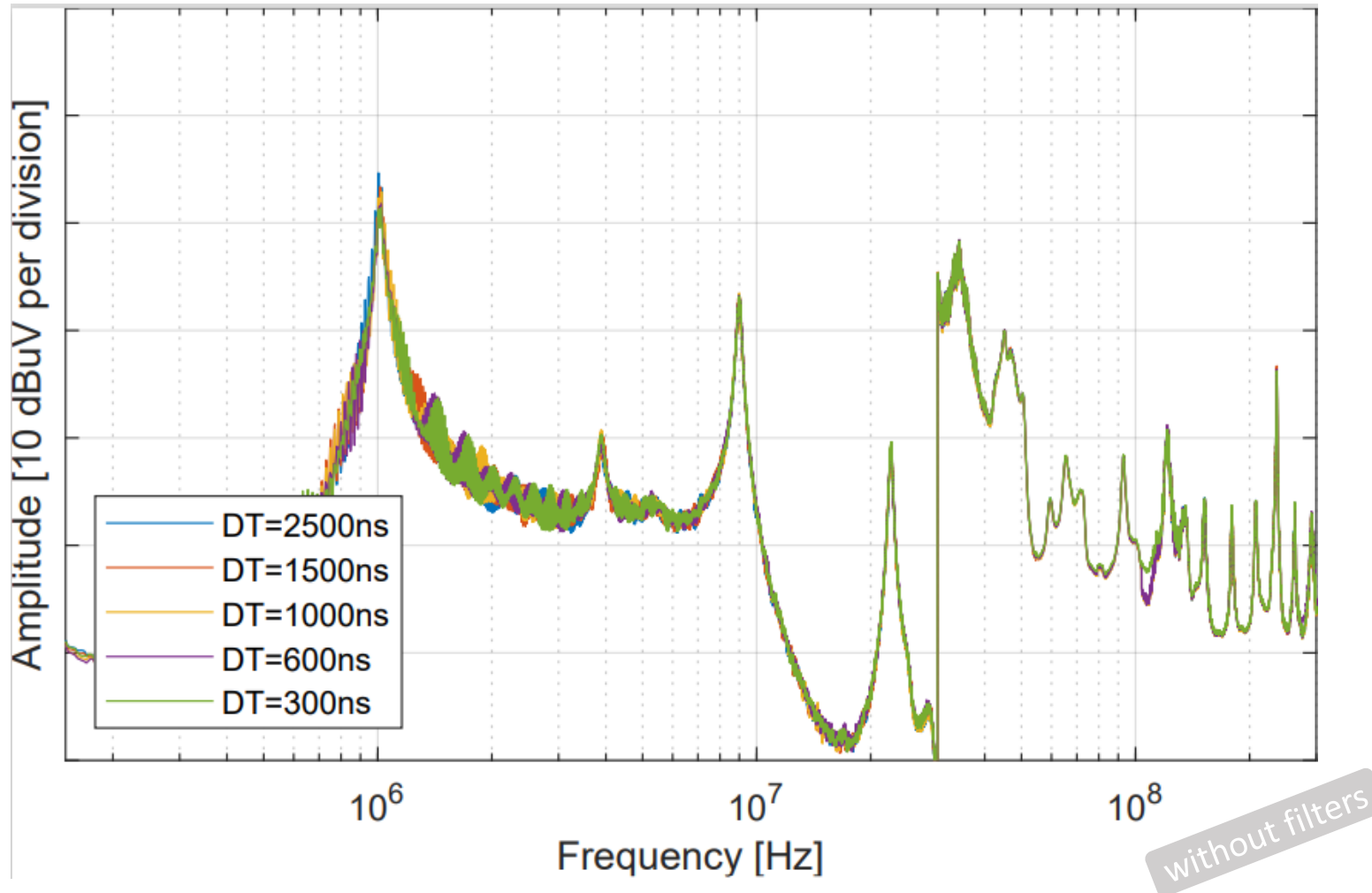
Slew rate control makes use of different conducted emission trends, by increasing switching speed for low currents



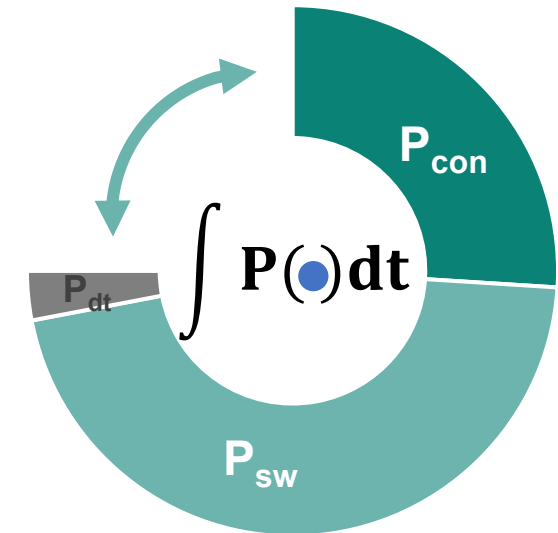
Loss reduction with optimized
slew rate control



Dead time optimization does not effect conducted emissions, but improves inverter efficiency further



Loss reduction with optimized
slew rate control & dead time



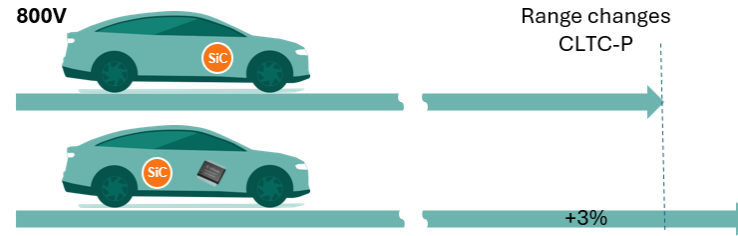
Semiconductor contribution to Performance & Efficiency of Automotive Traction Inverters



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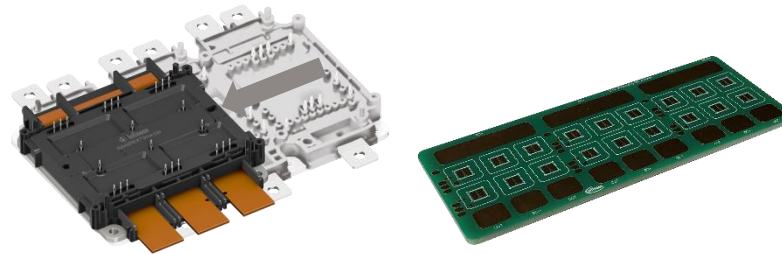
The Current State of Power Semiconductors in EV Design... ...and How It's Evolving

Slew rate control and **dead time optimization** brings inverter efficiency to more than 99%



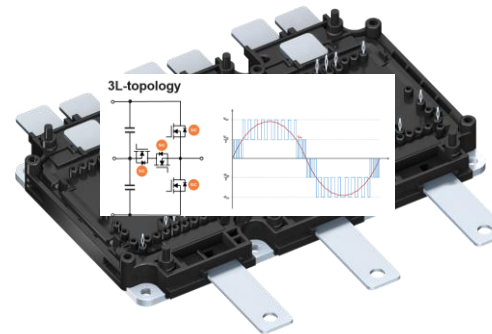
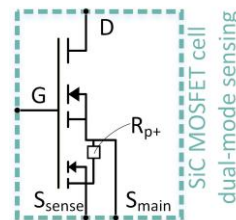
Trench super junction takes power density for SiC MOSFETs to the next level

GaN HEMT will offer an additional trade off point suited for future power devices



Faster switching will be enabled by **low inductance packaging**

Increased **temperature rating** along with **accurate sensing** will support system optimization



Further powertrain improvements focus on motor loss reduction with **multi level topologies**

Semiconductor Contribution to Performance & Efficiency of Automotive Traction Inverters

Thank you for your attention!