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Performance Parameters of SiC MOSFETs for Automotive Inverters

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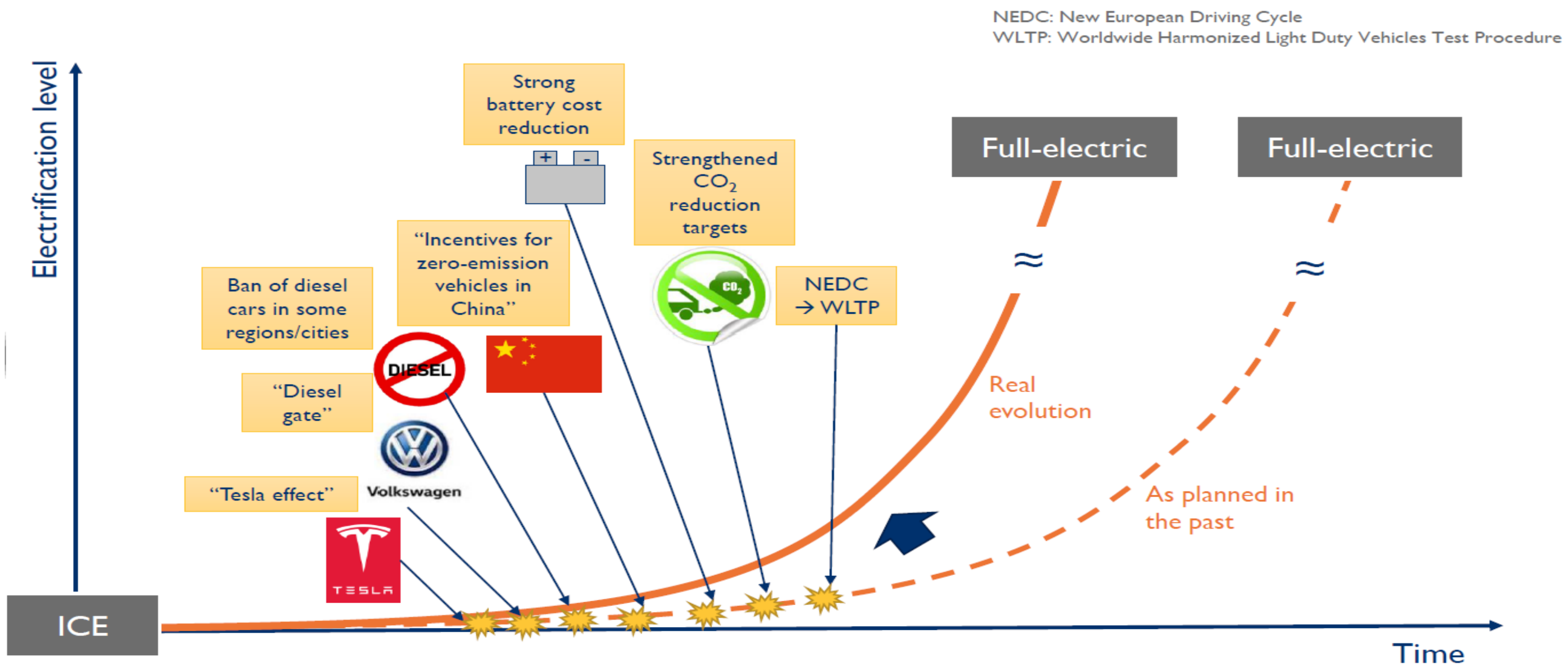
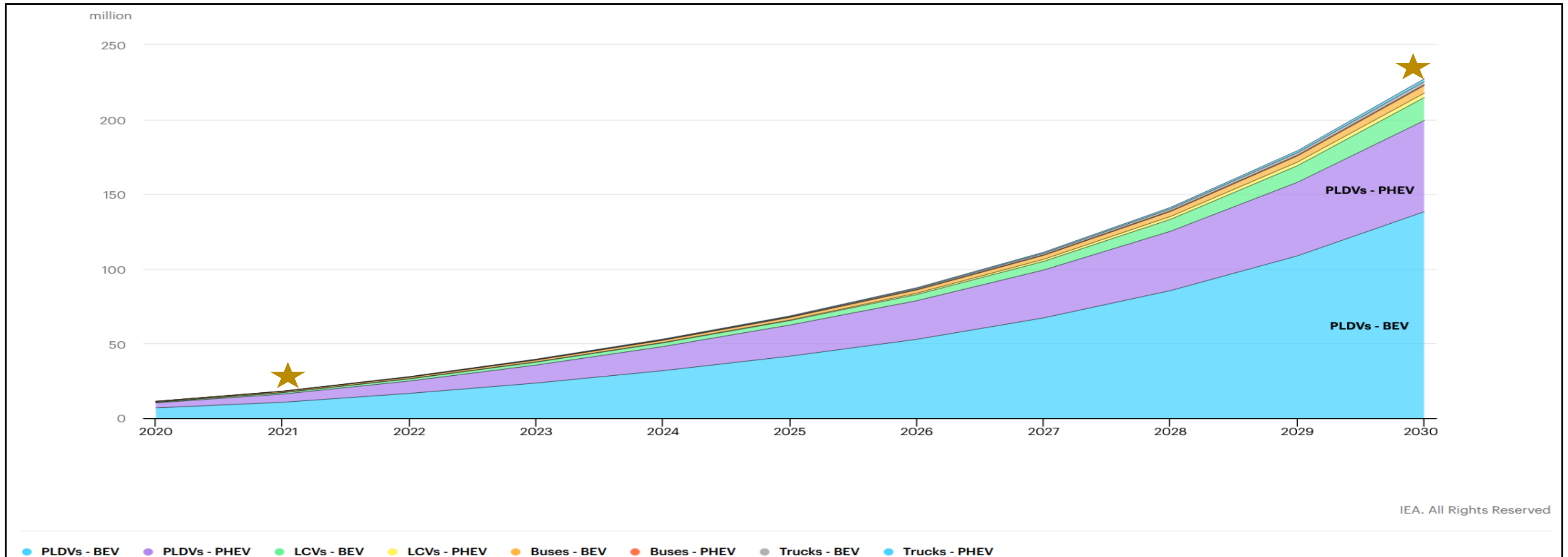
Vehicle Electrification Trends





- About 200 million electric vehicles expected on road by 2030
- Market share of EVs expected to exceed 30% by 2030
- ~9 % of global new car sales in 2021 were electric vehicles

Silicon Carbide (SiC) – Key Applications in Electric Vehicles

Traction Inverters

On-Board Charger (OBC)

DC-DC (HV→48V ; HV → 12V)

Extreme Fast Charger (XFC)

- ✓ SiC technology is revolutionizing vehicle electrification

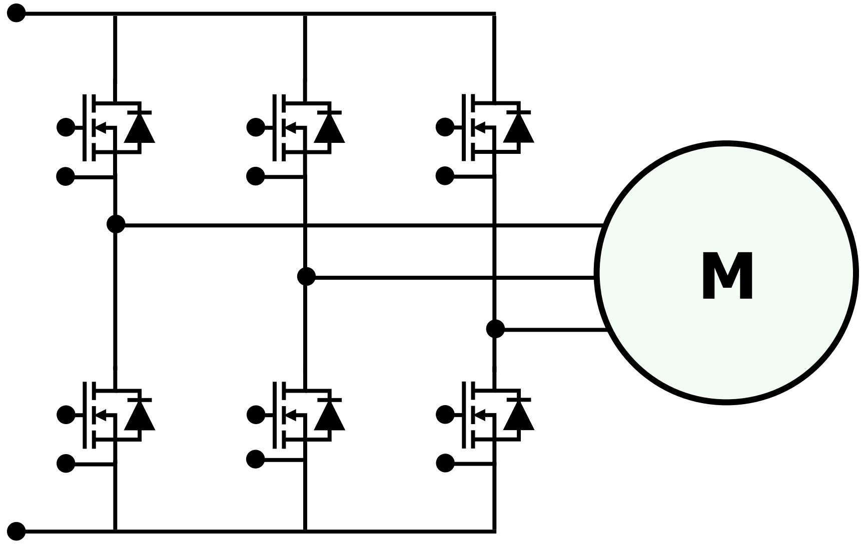
  Higher Voltage → *Greater Power* → *Better Efficiency* → *Smaller Size* → *Lighter Weight*

- ✓ SiC is proven significantly better than conventional silicon power device based solutions

- ✓ No longer a question of Si IGBT v/s SiC MOSFET in traction inverters !

  All leading OEMs adopting SiC

SiC MOSFET in EV/HEV Traction Inverters



3-Phase Inverter Based on SiC MOSFETs

- ✓ Nominal power ranging from 10 kW (ICE assistance) to 200 kW (pure EV)
  V_{BUS} : 400 V – 450 V → **750V SiC MOSFET**
  V_{BUS} : 700 V – 800 V → **1200V SiC MOSFET**
- ✓ Bi-directional operation (feeding electric motor + regenerative braking)
- ✓ 80% or more reduction in total inverter losses when compared with silicon-based (IGBT) solutions (same voltage, same switching frequency, same cooling)

SiC MOSFET Technologies – As it Exists Today

- **Do all SiC MOSFET technologies existing in the market offer similar performance, robustness and quality ?**

  SHORT ANSWER = **NO**

  There are significant differences at the power device technology level and power electronics designers must perform thorough evaluation/assessment of each SiC MOSFET technology to maximize their system performance and robustness.

- **Which SiC MOSFET Parameters Differ by Each Vendor / Technology and how do they affect the performance ?**

  NEXT SLIDE …..

750V SiC MOSFET Technology Comparison

Superior power density and cooler operation

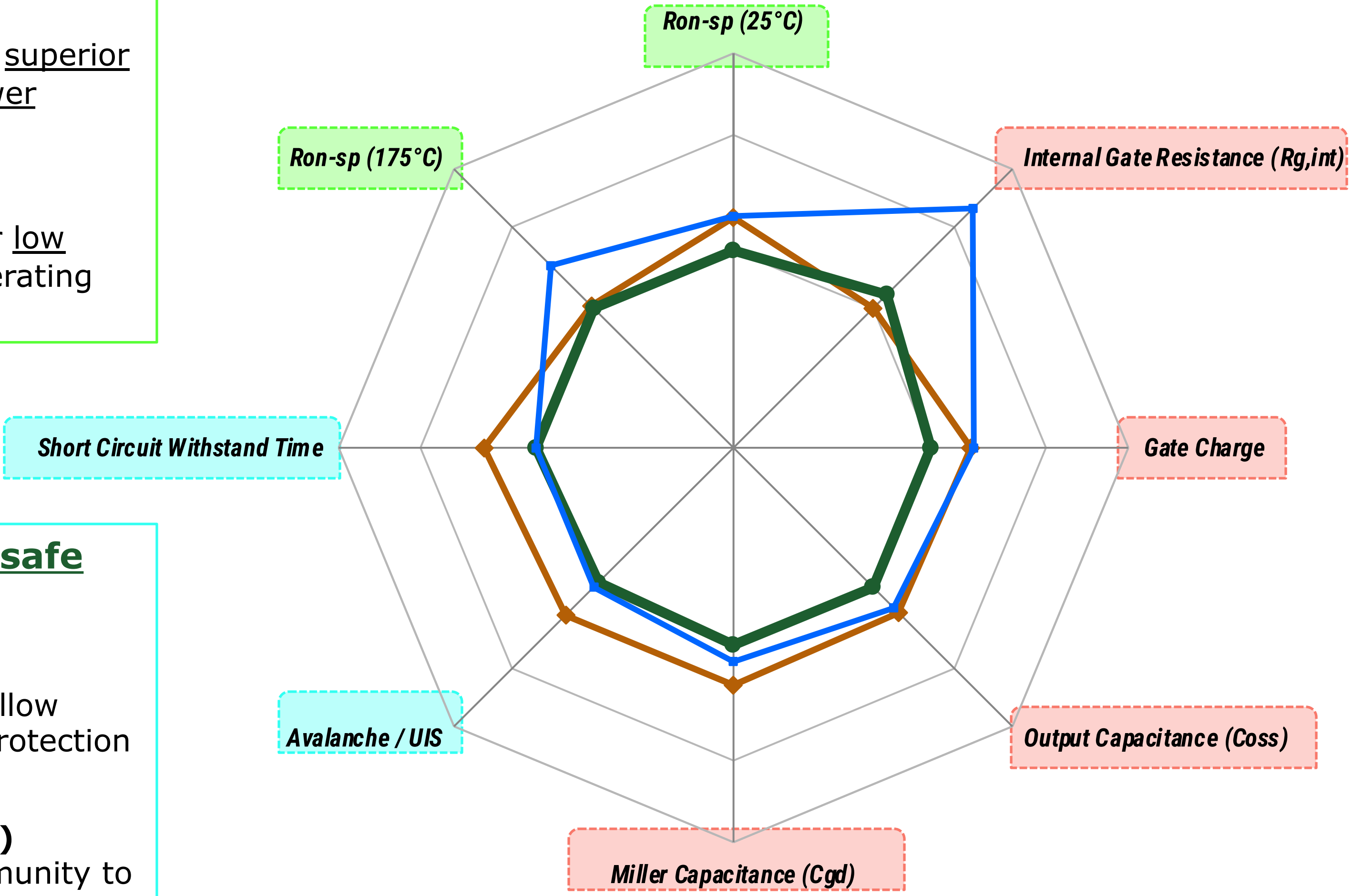
Industry-leading CPI for superior performance and more power desity

Softest temperature dependence of $R_{DS(ON)}$ for low conduction losses at all operating temperature

More robust and fail-safe designs

Improved short circuit withstand capability to allow designers develop robust protection circuits

Superior avalanche (UIL) ruggedness for better immunity to over-voltage transients. All production parts are **100% UIL tested**



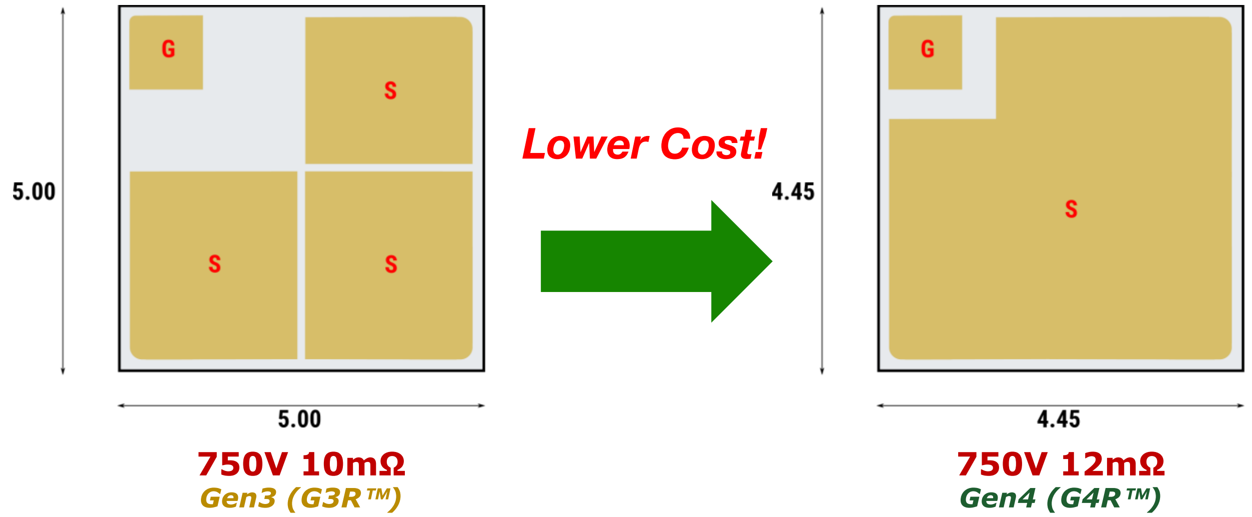
Faster and cleaner switching (lower switching losses)

Low $R_{g,int}$ and **low gate charge (Q_g)** to enable faster switching (lower losses)

Low device capacitances (C_{oss} and C_{rss}) to reduce ringing (lesser spikes) and lower switching losses

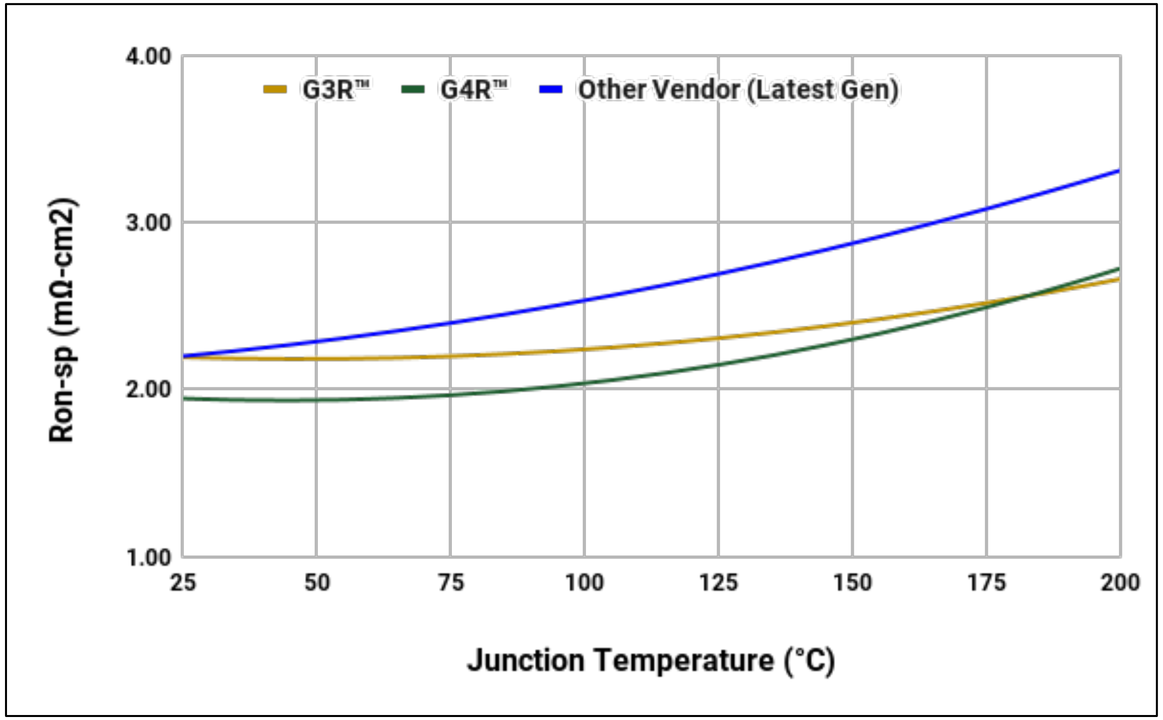
G4R™ (750V 12mΩ ; 19.8 mm²) v/s G3R™ (750V 10mΩ ; 25 mm²) v/s Other Vendor - Latest Gen (750V 10.5mΩ ; 25 mm²)

Specific On-State Resistance (R_{ON-SP}) v/s Temperature



	G3R™	G4R™	Other Vendor
V_{DSS}	750 V	750 V	750 V
Chip Size	5.00 mm x 5.00 mm	4.45 mm x 4.45 mm	5.00 mm x 5.00 mm
$V_{GS(op)}$	+15 V / -5 V	+15 V / -5 V	+ 15 V / -4 V
$R_{DS(ON)}$ @ 25°C	10 mΩ	12 mΩ	10.5 mΩ
$R_{DS(ON)}$ @ 175 °C	11.5 mΩ	15 mΩ	14.8 mΩ

Specific On-State Resistance, R_{ON-SP} (mΩ-cm²)

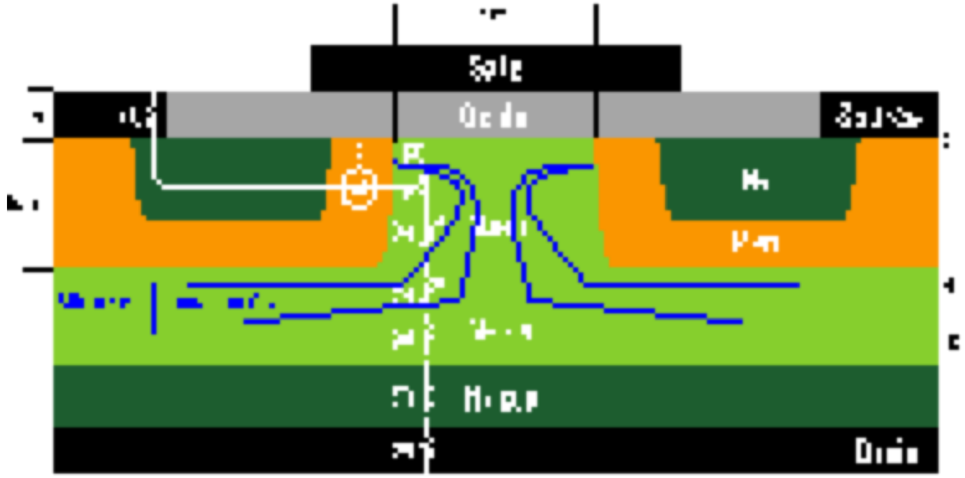


Requirements for Better Efficiency in all Drive Cycles (all Load Conditions) :

- ✓ Low Ron-sp (mΩ-cm²) at all temperatures (T_J)
- ✓ Cleaner switching performance and lower switching losses

  i.e. Low Gate Charge (Q_G), Low Internal Gate Resistance, Low C_{RSS}, Low Q_{OSS}, Low Q_{RR}

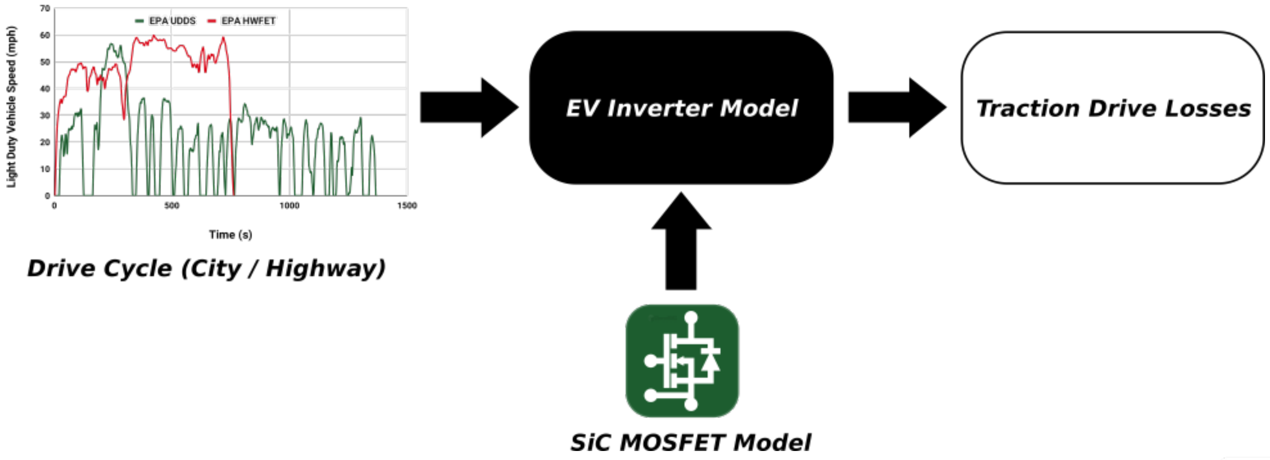
Physics-Based SPICE Model for Reliable Circuit Simulations



- ✓ Sophisticated and accurate physical model
- ✓ Scalable – device design and process parameters included
- ✓ Straight forward model parameter definition process
- ✓ Easy measurement-based calibration
- ✓ Covers the wide operating temperature range of SiC MOSFET
- ✓ Accurate modeling of gate-bias and drain-bias dependencies
- ✓ Compatible with commercially available SPICE software suites
- ✓ Low computational effort and high efficiency

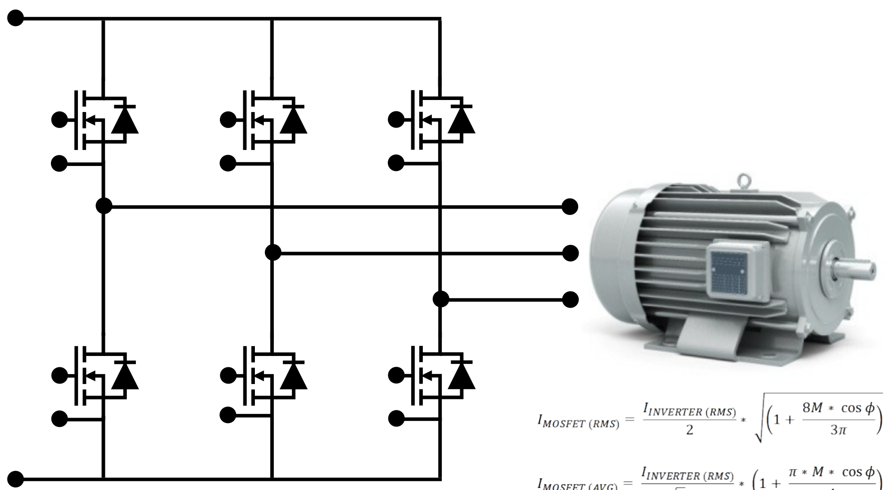
On-Resistance Components

(1)	R_{source}	Source metal resistance
(2)	R_{ch}	Channel resistance
(3)	R_{acc}	Accumulation region resistance
(4)	R_{JFET}	JFET region resistance
(5)	$R_{drift\text{-}var}$	Bias-dependent drift layer resistance
(6)	$R_{drift\text{-}con}$	Drift layer resistance
(7)	R_{sub}	Substrate resistance
(8)	R_{drain}	Drain metal resistance



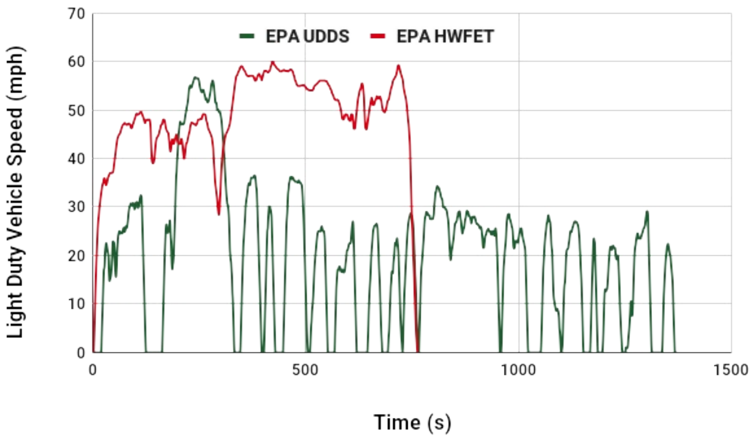
Splitting of $R_{DS(ON)}$ components is necessary to realize accurate temperature, gate-bias and/or drain-bias dependencies

Reducing Power Device Losses in Traction Inverters



$$I_{MOSFET\,(RMS)} = \frac{I_{INVERTER\,(RMS)}}{2} * \sqrt{\left(1 + \frac{8M * \cos\phi}{3\pi}\right)}$$

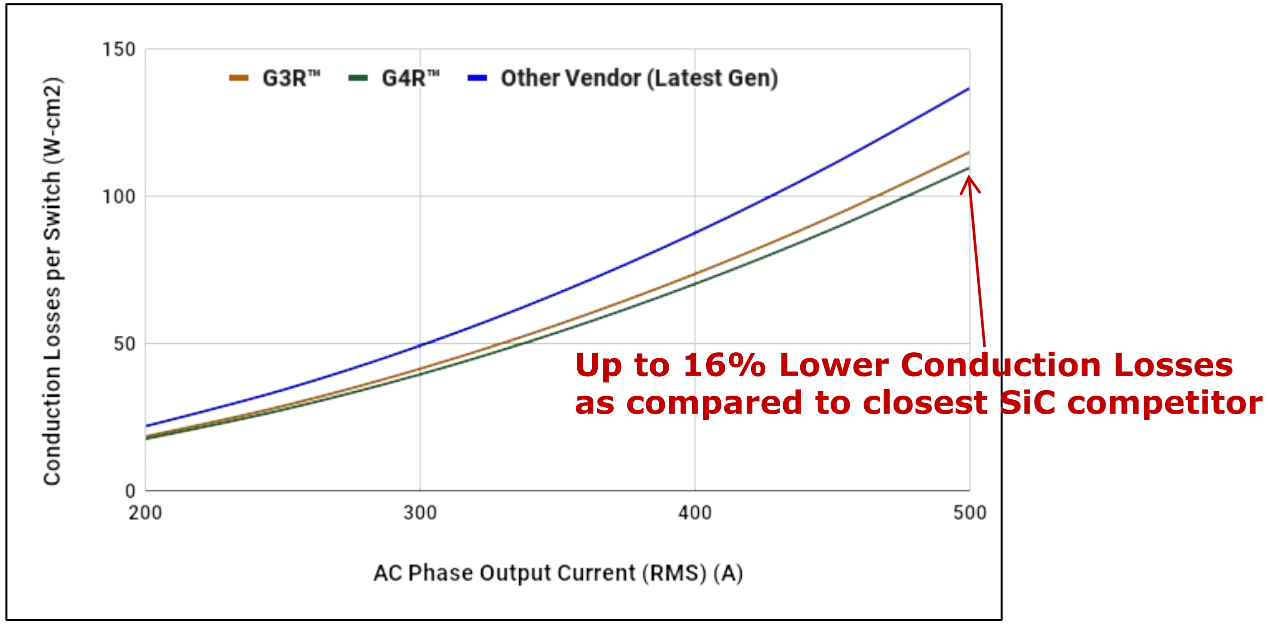
$$I_{MOSFET\,(AVG)} = \frac{I_{INVERTER\,(RMS)}}{\sqrt{2} * \pi} * \left(1 + \frac{\pi * M * \cos\phi}{4}\right)$$



3-Phase Traction Inverter (Synchronous Rectification) SVPWM (m = 0.8 ; cosφ = 0.8)
DC-Link Voltage = Up to 475V DC
Switching Frequency = 10 kHz

Conduction Losses per Switch (W-cm²)

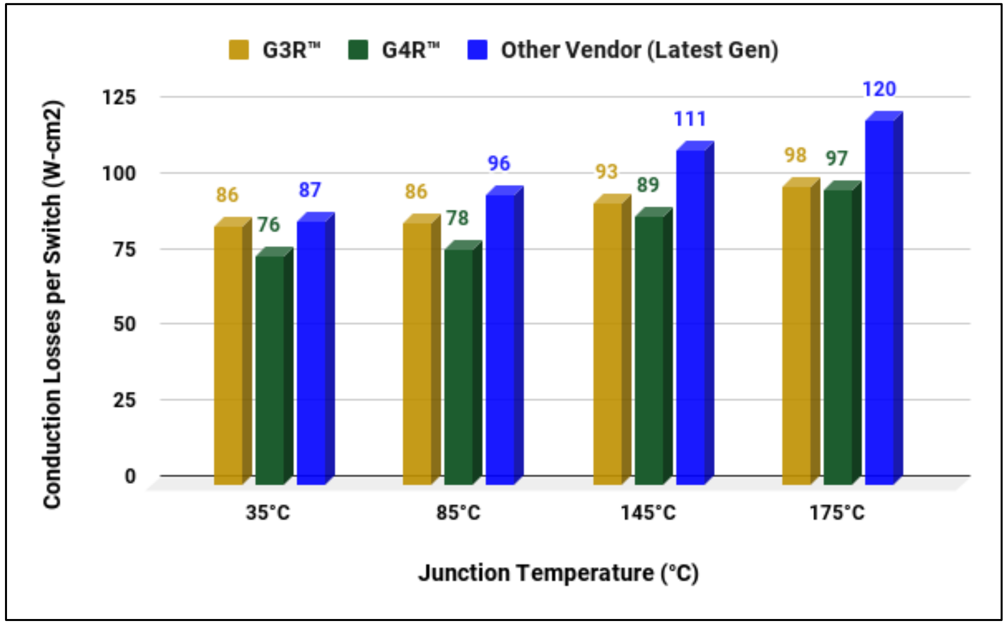
(Normalized to chip area in cm²) (T_J = 145°C)



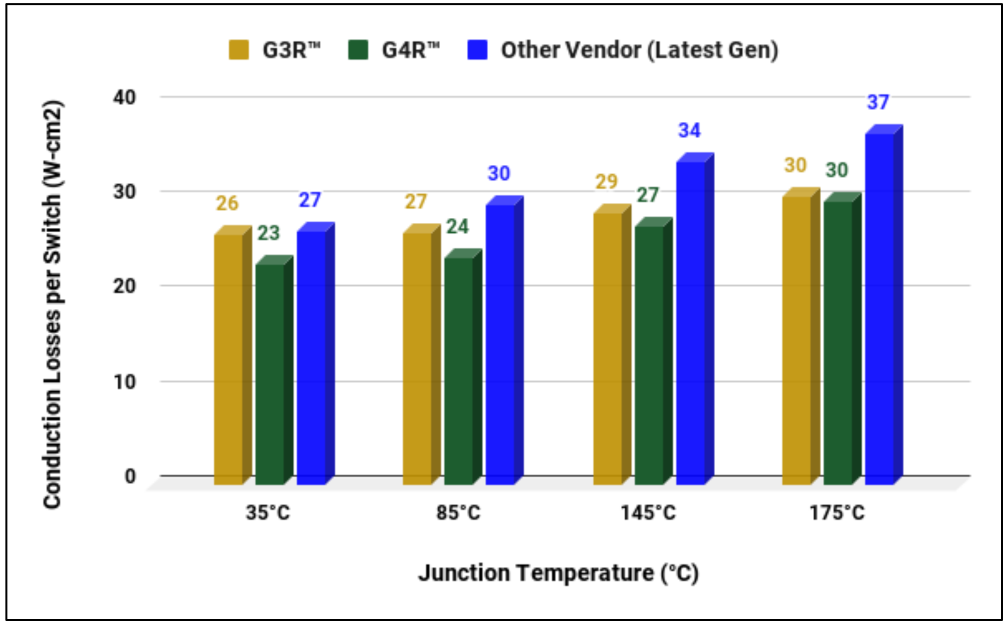
✓ Lowest possible conduction losses can be achieved by SiC MOSFETs with lowest Ron-sp (mΩ-cm2) and **softer temperature dependence of $R_{DS(ON)}$ (Better Temperature Coefficient)** for all drive cycles – *Urban Dynamometer Driving Schedule (UDDS) ; Highway Fuel Economy Test (HWFET)*

Superior Drive Cycle Efficiency with Better SiC MOSFET Technology

Conduction Losses per Switch (W-cm²)



I_{RMS} = 450 A
(AC Phase Output Current; 3-Ph Inverter)



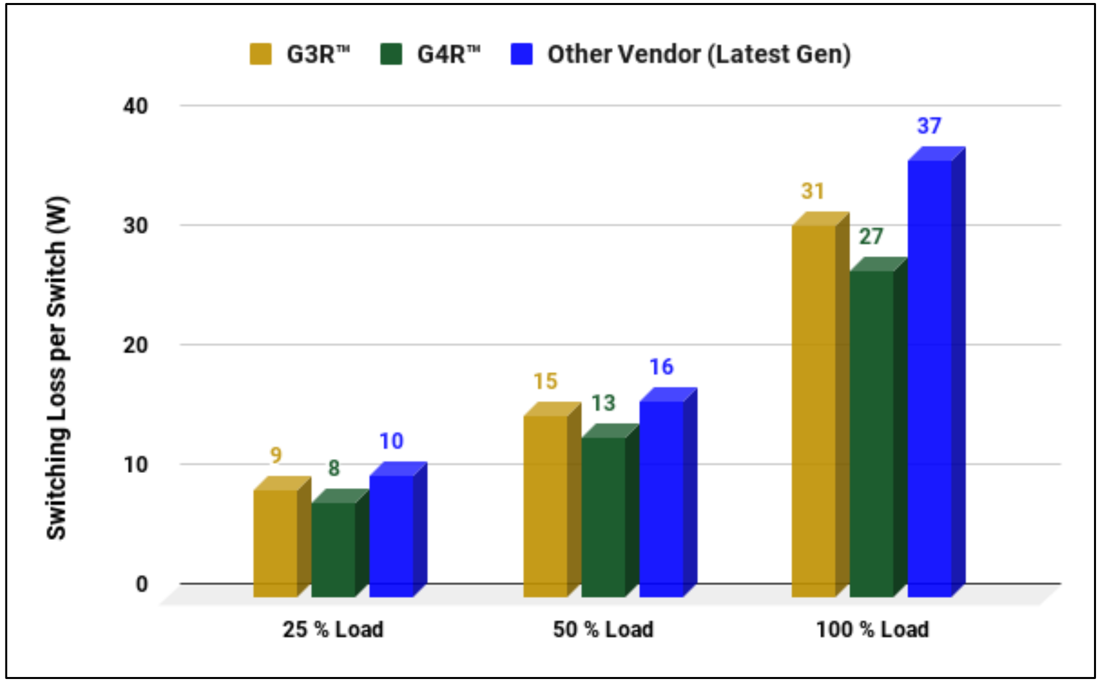
I_{RMS} = 250 A
(AC Phase Output Current; 3-Ph Inverter)

- ✓ Light-Load Condition (I_{RMS} = 250A)
  - ➢ ~18% reduction in conduction losses possible when temperature (T_J) is in the 85°C – 145°C range.
  - ➢ ~20% reduction when operating temperature is in the 145°C – 175°C range
- ✓ Heavy-Load Condition (I_{RMS} = 450A)
  - ➢ ~20% reduction in conduction losses possible when temperature (T_J) is in the 85°C – 175°C range.

G4R™ (750V 12mΩ ; 19.8 mm²) **v/s G3R™** (750V 10mΩ ; 25 mm²) **v/s Other Vendor - Latest Gen** (750V 10.5mΩ ; 25 mm²)

Superior Drive Cycle Efficiency with Better SiC MOSFET Technology

Working Load v/s Switching Losses per Switch (W) ; f = 10 kHz



FULL LOAD – 100 %

I_{RMS} = 450 A *(AC Phase Output Current; 3-Ph Inverter)*

I_{RMS-SW} = 280 A (Per Switch Position)

(4 Paralleled Dies per Switch Position; 70A RMS per Die)

NOMINAL LOAD – 50%

I_{RMS} = 250 A *(AC Phase Output Current; 3-Ph Inverter)*

I_{RMS-SW} = 155 A (Per Switch Position)

(4 Paralleled Dies per Switch Position; 38A RMS per Die)

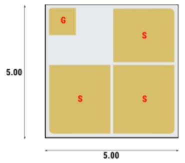
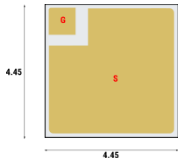
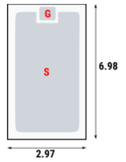
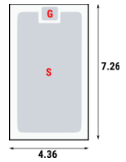
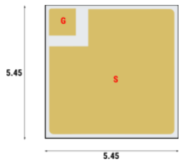
- ✓ Full Load Condition
  - ➢ ~25% reduction in switching losses possible (comparing G4R™ v/s closest SiC competitor)
- ✓ Nominal Load Condition
  - ➢ ~18% reduction in switching losses possible (comparing G4R™ v/s closest SiC competitor)

G4R™ (750V 12mΩ ; 19.8 mm²) **v/s G3R™** (750V 10mΩ ; 25 mm²) **v/s Other Vendor - Latest Gen** (750V 10.5mΩ ; 25 mm²)

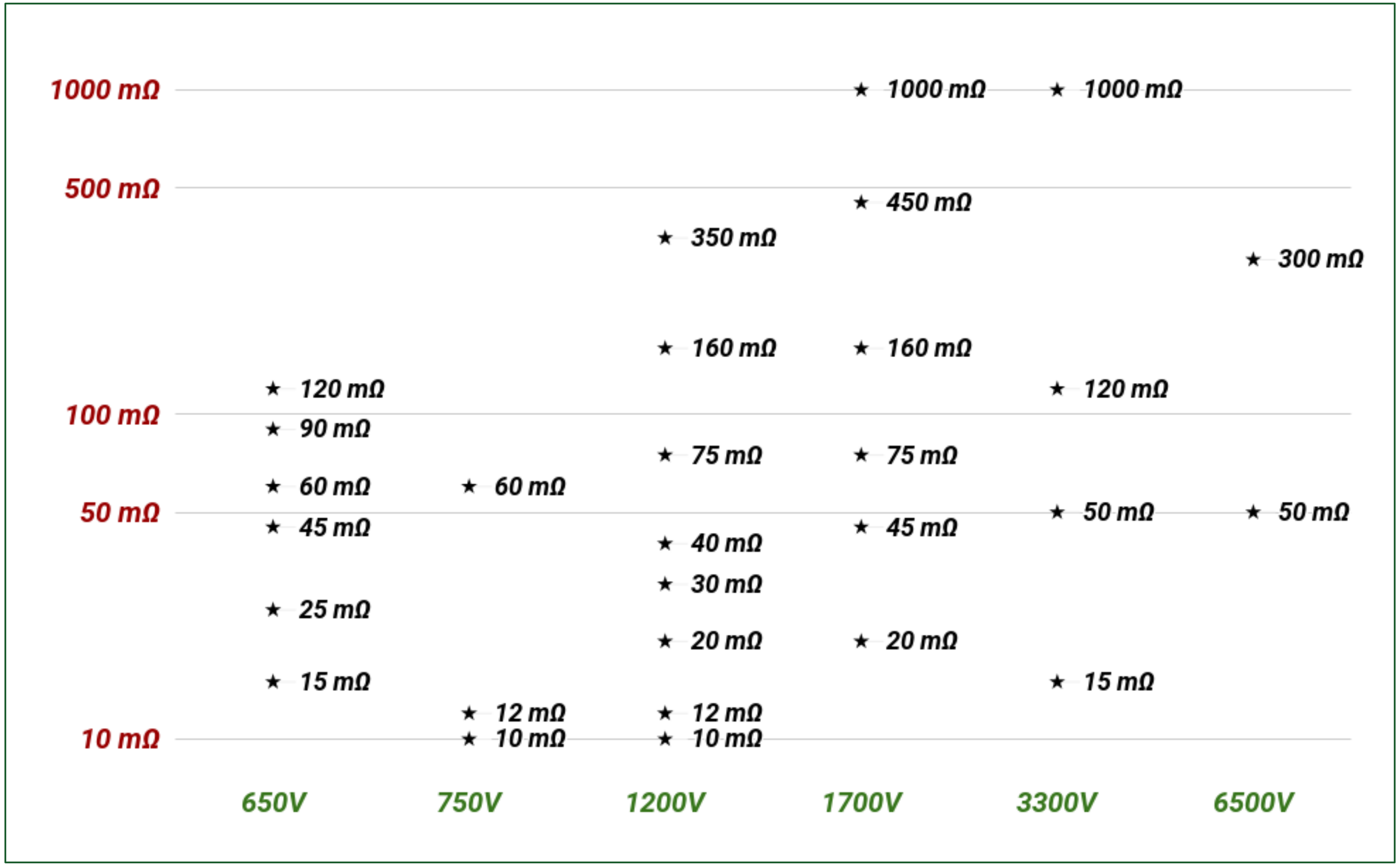
Criteria to Judge SiC MOSFETs

METRICS	*WHAT IS REQUIRED ?*	*HOW TO ASSESS ?*
Performance	• Superior Figure-of-Merit (FoM) • Efficient and Cooler Operation under all Conditions	✓ Low $R_{ON(SP)}$ ✓ Better Temperature Coefficient of $R_{DS(ON)}$ ✓ Better Switching Performance
Robustness	• Avalanche Robustness • Short-Circuit Robustness	✓ Sufficient E_{AS} Rating ✓ Sufficient Short Circuit Withstand Time
Reliability	• No V_{TH} Drift (Reliable Gate Oxide) • Stable Performance under Body Diode Operation	✓ V_{TH} Stability Under NBTS and PBTS ✓ DIBL Effect (V_{TH} v/s V_{DS}) ✓ Body Diode Reliability
Quality	• Robust manufacturing process • Automotive-qualified production line	✓ Tight V_{TH} and $R_{DS(ON)}$ Distribution
Price	• Competitive price and Fast turn-Around • Supply Chain Stability and Superiority	✓ Low $R_{ON(SP)}$ for Lower Cost ✓ Robust Supply Chain ✓ Capacity and Turn-Around Times

SiC MOSFET Bare Chips for EV/HEV Traction Inverters

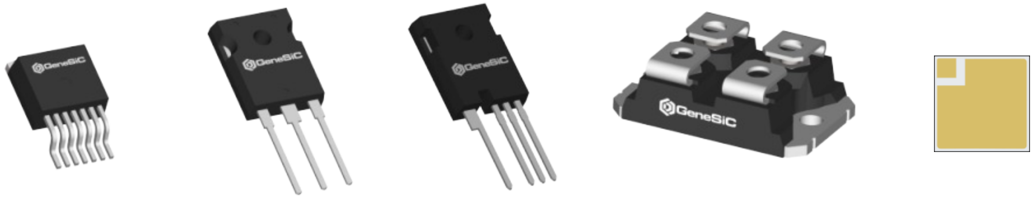
		P/N	Technology	Metallization	Image
750V	*10 mΩ*	G3R10MT07-CAU	G3R™	Top-Side : Ni+Pd+Au Back-Side : Ni+Pd+Au	
	12 mΩ	G4R12MT07-CAU	G4R™	Top-Side : Ni+Pd+Au Back-Side : Ni+Pd+Au	
1200V	*20 mΩ*	G3R20MT12-CAL	G3R™	Top-Side : Al Back-Side : Ni+Ag	
	12 mΩ	G3R12MT12-CAL	G3R™	Top-Side : Al Back-Side : Ni+Ag	
	10 mΩ	G4R10MT12-CAU	G4R™	Top-Side : Ni+Pd+Au Back-Side : Ni+Pd+Au	

Most Comprehensive SiC MOSFET Portfolio – 650V to 6500V



50+ SiC MOSFET Products

- ✓ **650V/750V** → 10 mΩ to 120 mΩ
- ✓ **1200V** → 10 mΩ to 350 mΩ
- ✓ **1700V** → 20 mΩ to 1000 mΩ
- ✓ **3300V** → 15 mΩ to 1000 mΩ
- ✓ **6500V** → 50 mΩ to 300 mΩ



Questions

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