SIC FETs in EV applications

The allure of silicon carbide for all types of electromobility applications

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Abstract

Wide bandgap semiconductors are finding applications in all types of power conversion including in electric vehicles. With their promise of higher efficiency and faster switching speeds yielding potential savings in cost, size and energy, WBG devices are commonly used in chargers and auxiliary converters but have yet to displace IGBTs in traction inverters in significant volume. This white paper explains how the latest-generation SiC FETs are ideally suited to new inverter designs with lower losses than IGBTs and proven robustness against short circuits, even at high temperatures and under repetitive stress.

38% of US cars in the year 1900 were electric vehicles

Yes, you read that right; of all US automobiles in 1900, 38% were powered by electricity, 40% by steam and just 22% by gasoline [1]. However, when Henry Ford mass-produced cheap gas-powered cars, the percentage diminished dramatically and the earliest electric vehicles (EVs) all but disappeared. Today the percentage of EVs on the roads is currently less than 1%, but it is predicted that 65%-75% of light-duty vehicles in the US will be electrically powered by 2050 [2]. More widely, the International Energy Agency predicts that EVs will form 25% of vehicles on the road globally by 2025 (**Figure 1**) and the Clean Energy Ministerial (CEM), with its eye on the transportation sector accounting for nearly one quarter of greenhouse gas emissions, aims to see new EV sales at 30% of the car market in CEM-participating countries by 2030, with its EV30@30 campaign [3].

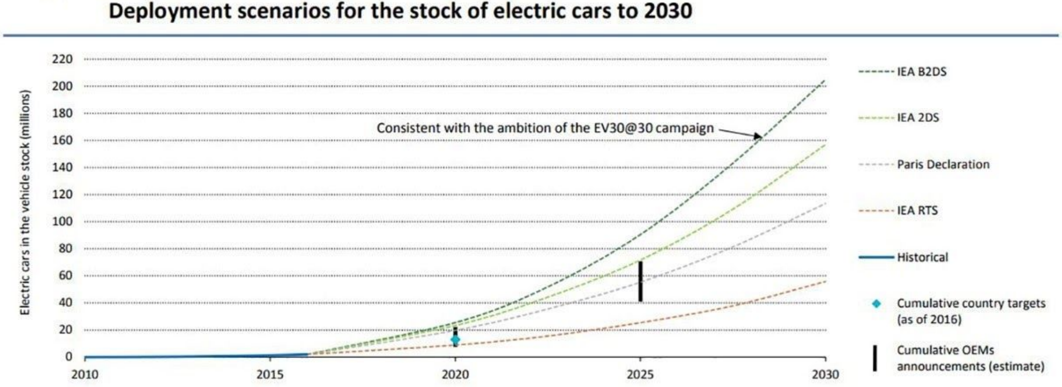

***Figure1:** Deployment scenario for the stock of electric cars to 2030.*
Source: IEA Global EV outlook (2017)

Modern EVs have improved dramatically since the Toyota Prius hit the Japanese streets in 1997 with sophisticated battery and motor technologies now offering a range of 300 miles and more. The uptake of EVs predicted for 2050 does however rely on certain assumptions: purchase affordability, continuing high oil prices, stricter health and environmental regulations and further technological advances for better range and quicker charging.

All About Efficiency

An EV has a conversion efficiency ranging between 59% and 62% from battery energy to power at the wheels, seemingly giving some scope for improvement. Engineers of electrical drives might take pains to point out that the motor itself isn't more than 85-90% efficient and add that the modern internal combustion engine is struggling to achieve 21%, but at least there is a possible roadmap for better performance from EVs with new semiconductor switches available to use in the drivetrain. Key to better range is the efficiency of power conversion. This is not just in the motor drive electronics – since significant energy is used in auxiliary functions such as lighting, A/C and even infotainment, much effort has gone into reducing the draw from these areas, such as by replacing inefficient traditional lights with LEDs. The various power converters that step down the main battery voltage, typically 400 V, to 12 V or 24 V for these functions now can include the latest topologies and exotic semiconductors to achieve best efficiency with the risks inherent in new technology acceptable with non-safety-critical applications (**Figure 2**).

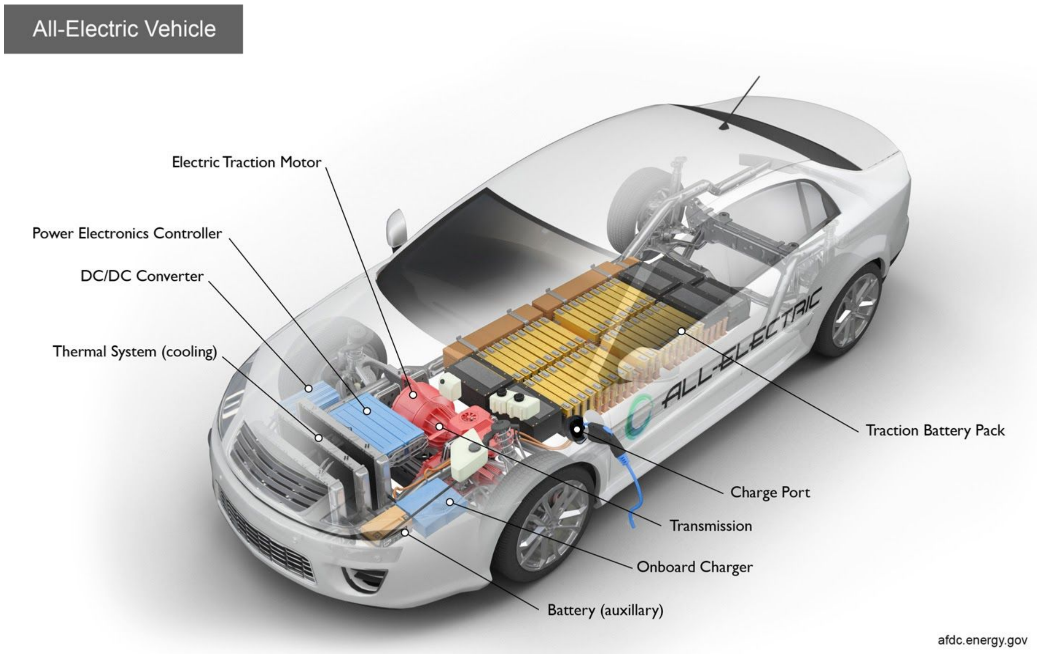

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Figure 2: *Power conversion components in an electric vehicle.*

For the drivetrain, the motor control electronics is seen as life-critical, so designers have opted to ‘play safe’ and stick to tried-and-tested technologies. In practice, this has meant using IGBT switches which have proven their robustness over more than 30 years. For example, beneath the high-tech exterior of a Tesla model S are 66 IGBTs in TO-247 packages controlling the traction motors - the very same IGBT technology you would have seen in a 1980s industrial process controller. In EVs, the IGBTs switch at around 8 – 12kHz. Frequency is kept this low as high-power IGBTs show rapidly increasing losses at higher switching rates. The low switching speeds are beneficial in maintaining low dV/dts at the motor windings, but the higher current ripple causes more iron losses. However, newer cars have just started to use wide band-gap (WBG) semiconductors in place of IGBTs and there is now a promise of increasing switching frequency as well as improving that 62% efficiency figure.

Wide bandgap semiconductors are now contenders in EV motor control

IGBTs have already been replaced in many modern power applications such as in PV inverters, UPSs and EV onboard chargers, with newer technologies such as silicon Superjunction MOSFETs and now WBG semiconductors fabricated in silicon carbide (SiC) and gallium nitride (GaN) materials. Although MOSFETs are a well-established technology, they have made little headway in EV traction applications compared with IGBTs, as the necessary high-voltage types have relatively high losses and poor body diode recovery characteristics. WBG switches however, have low inherent losses at high voltages and a host of other advantages and are now finding increasing use in EV motor drives.

Wide-band-gap semiconductor primer

WBG semiconductors in SiC and the more recent GaN technologies have a fundamental advantage over silicon in that the energy required to move electrons from atomic valence bands to conduction bands is much higher, for example 3.2 eV (electron-volts) for SiC, compared with 1.1 eV for silicon. This translates to higher electric field breakdown performance for a given material thickness and also ability to withstand higher temperatures before destruction, typically instantaneous peak temperatures allowed over 600°C, depending on the device. SiC also has a thermal conductivity about 3.5 x better than silicon which all adds up to a much smaller die for a given current and voltage rating. Smaller die have naturally much lower capacitances, so WBG devices can switch at high speed with low loss in power applications at high temperatures. Switching frequency can be kept low to enable the lowest possible switching losses but if it is pushed up, other benefits appear – filter inductors become smaller and capacitors around the circuit reduce in value and size. Even at higher frequencies there still can be net efficiency savings, resulting in less power dissipation and consequently smaller and cheaper heatsinks. The net effect can be a more efficient, lighter and smaller product with significant cost savings.

There are more advantages to be taken as well at a system level; the high temperature ability of WBG devices allows traction inverters now to be integrated into motor housings with significant cost, reliability and size savings over having separate drive electronics with interconnections to the motor. The motor control is also improved at higher switching frequencies with smoother current waveforms giving less noise and vibration, and improved motor efficiency. Additionally, IGBTs require a ‘free-wheel’ diode in parallel in motor drive applications – this can be omitted in some schemes using WBG switches with their integral body diodes saving yet more cost and assembly labor.

SiC FETs in the family of WBG switches

Silicon carbide and gallium nitride are simply materials suitable for the fabrication of different types of power semiconductor devices such as diodes, MOSFET and JFETs in SiC and HEMTs in GaN. All are available on the market with their own ‘sweet spot’ applications. For switches, SiC MOSFETs and GaN HEMTs are high-performance but their gate drive requirements are very exacting. A GaN HEMTT does not have an effective body diode while the SiC MOSFET diode is fast but has a high forward voltage drop, often necessitating the use of an external diode anyway.

JFETs in SiC and GaN are useful in that they do not have a fragile gate oxide. They can be built as normally-on or normally-off types. The normally-On types have the lowest chip resistance per unit area but they need a negative gate voltage to hold the switch OFF. Most circuit architectures have been developed for normally-off devices, so there is no provision to manage the shoot through condition that would occur if both normally-on JFETs in a bridge lost gate power. They also don’t have body diodes. There is one particular type of WBG device that overcomes the shortcomings - the SiC FET, a composite or ‘cascode’ of a SiC JFET and a Si MOSFET, which is normally-OFF with no bias and can switch in nanoseconds (**Figure 3**).

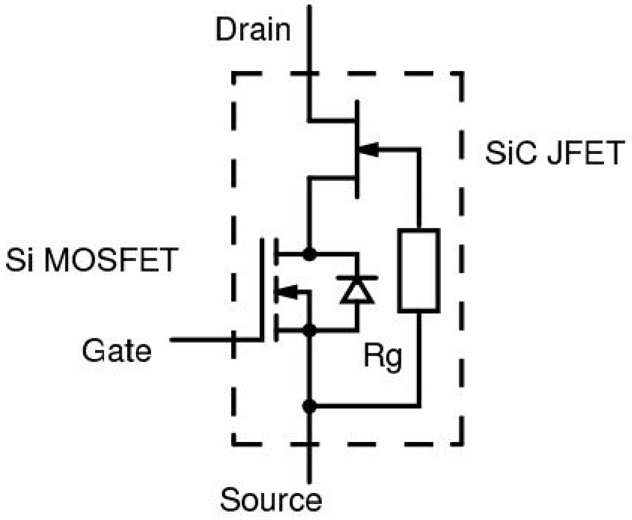

Figure 3: *SiC FET ‘cascode’ of SiC JFET and Si-MOSFET.*

SiC FETs in electric vehicles drives

So why have these miracle devices not made inroads into EV motor control when there is a drive for higher performance solutions? Apart from the natural conservatism of car system designers, there are some practical reasons: a WBG device is seen as expensive compared with an IGBT of similar ratings; the load on the drive inverter is the motor, whose inductance does not scale down as in DC-DC converters, making higher switching frequencies less attractive. The high switching speed means high dV/dt rates that stress the insulation of motor windings. High dV/dt can also cause problematic EMI and even motor bearing wear due to ‘Electrical Discharge Machining’ or EDM caused by common-mode noise current finding a path to ground through the motor bearings. Importantly, as the technology is relatively new, there is also a nagging doubt about the proven reliability of WBG devices generally, under the harsh conditions of an automotive motor drive with its potential short-circuits, back-EMFs and general high-temperature environment.

The possibility of improving efficiency is still a tempting prospect though. In an EV motor drive this translates to more available energy and better range. Heatsinks can be smaller, reducing costs and weight, which again in turn helps extend range – a ‘virtuous circle’. With SiC FETs, efficiency is particularly improved under typical operating conditions. SiC FETs are simply a resistance when on, compared with IGBTs which have a ‘knee’ voltage, giving effectively a minimum power loss that is ubiquitous under all driving conditions. This is shown in **Figure 4** below, where we compare 200 A, 1200 V IGBT modules using two 1cm x 1cm IGBT die vs. a 200 A, 1200 V SiC FET module with two 0.6 x 0.6 cm SiC stack cascode die.

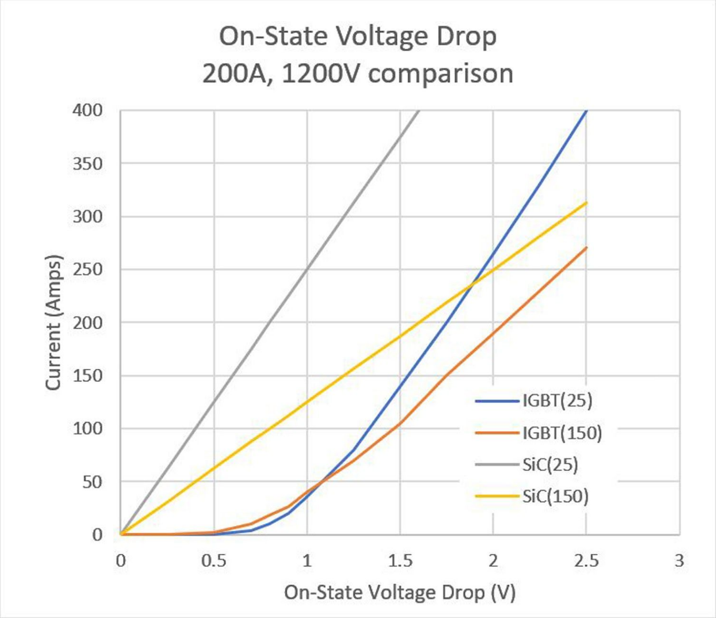

Figure 4: *Conduction loss for 1200 V SiC FETs with 36% of the comparison IGBT chip area. In this 200 A, 1200 V module, ON-state voltage drop with SiC FETs is much lower than the IGBT drop for all currents below 200 A, both at room and elevated temperatures.*

SiC FETs are available as standard with 650 V, 1200 V and higher ratings, matching nicely the current popular EV battery voltage of around 400 V and the upcoming 750 V versions.

SiC FETs are uniquely able to provide the lowest conduction losses in a given module footprint. For sure, in a ground-up design, a WBG motor drive could be switched at a higher frequency than with IGBTs, with sufficient EMI control designed-in, giving all the WBG benefits. Even cost should not be an issue going forward; the die of a SiC FET is much smaller than an IGBT or SiC MOSFET of equivalent ratings, meaning more yield per wafer. If the cost savings of smaller heatsinks and filters are factored in, along with the mounting energy savings with time and convenience of extended range, it all starts to make sound economic and practical sense.

SiC FETs have proven reliability

We're now left with those concerns about reliability - which for some WBG devices are very valid. For example, SiC MOSFETs and GaN devices are extremely sensitive to gate voltages with absolute maximum values very close to recommended operating conditions. SiC FETs on the other hand are tolerant of a wide range of gate voltages with wide margins to absolute maximums and parts are available with gate clamp diodes which provide another level of protection against overvoltage and ESD.

Short-circuit rating is perhaps the major concern in EV motor drives with IGBTs the benchmark for robustness. Certainly, GaN devices are poor performers here but once again, the SiC FET scores. SiC JFETs are known to have excellent short circuit handling, and since the SiC JFET in the cascode SiC FET controls the peak current, this makes the short circuit characteristics independent of gate drive voltage, unlike with SiC MOSFETs or IGBTs. The high peak temperature allowed with SiC JFET also allows extended short circuit durations. In automotive applications, there is an expectation that a short circuit should be withstood for 5μs before protection mechanisms kick in. Tests with 650 V SiC FETs from UnitedSiC show at least 8 μs withstand with a 400 V DC bus (**Figure 5**) with no degradation of ON-resistance or gate threshold after 100 short circuit events and at elevated temperature. Other tests with a 1200 V device at 850 V VDS (**Figure 6**), showed peak current under short circuit decreasing with initial junction temperature, reducing total energy dissipated, demonstrating the benign effect of the positive temperature coefficient of ON-resistance of the SiC FET. This effect also ensures that short-circuit current flow is uniform across the multiple cells in the die.

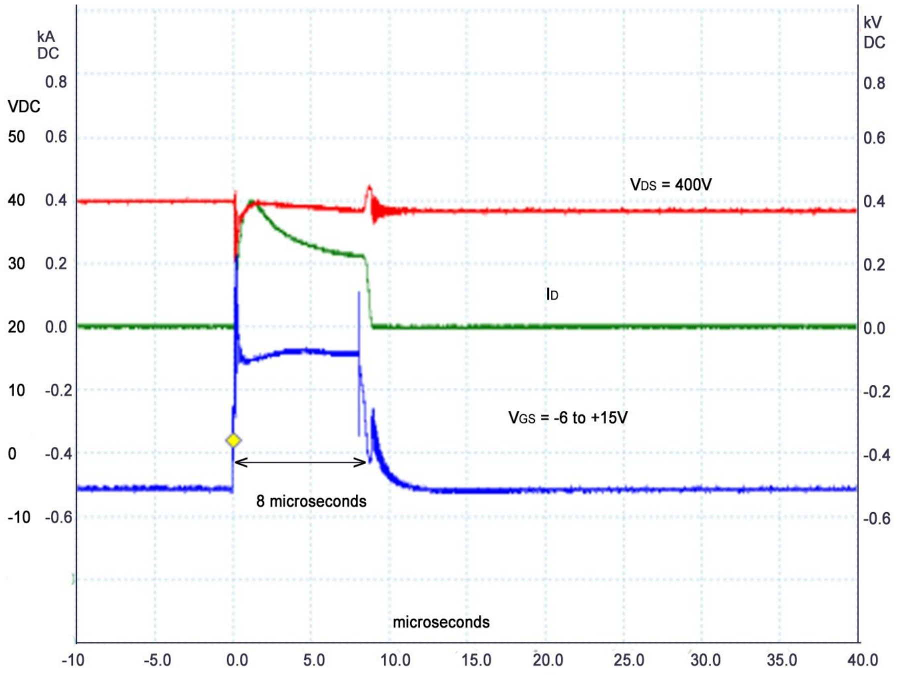

Figure 5: *Short circuit performance of SiC FET.*

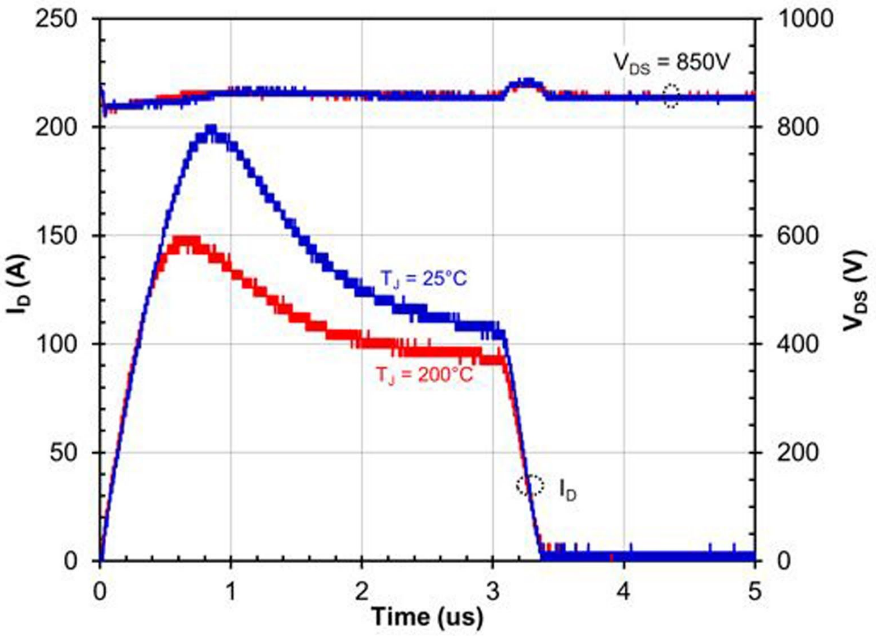

Figure 6: *SiC JFET is independent of initial junction temperature (UnitedSiC UJC1206K).*

SiC JFETs can be designed for a good tradeoff in automotive applications between the interdependent parameters of short-circuit current, on-resistance and turn-on speed.

The other stress that can occur is voltage spikes exceeding the maximum drain-source ratings. Again, GaN is not immune, but SiC FETs have very good avalanche ratings. The internal JFET gate-drain junction breaks over, passing current through RG in **Figure 3**, which then raises the SiC JFET gate-source voltage to the point where the threshold voltage of about -6 V is crossed. This turns the channel ON, clamping the over-voltage. The low-voltage Si-MOSFET also avalanches, but in UnitedSiC cascodes, there is an avalanche clamp diode built into every cell and due to the low breakdown voltage, energy dissipated in the Si-MOSFET causes little temperature rise. Tests by UnitedSiC show no failures with SiC FET parts in avalanche for 1000 hours at 150°C[4] with 100% production tests of avalanche capability as a backstop.

Any device designed into automotive applications needs to have the relevant approvals, AECQ-101 in the case of semiconductors. The tests performed for approval are listed in **Table 2** with results for the SiC FETs from UnitedSiC in TO-220-3L, TO-247-3L and their ‘Kelvin connection’ TO-247-4L packages. Simply put, no device failures or significant shifts in performance occurred across the sample sizes given. According to JEDEC standard JESD 85, this corresponds to a FIT rate (failures per billion hours) of better than 1.117 with an MTTF of better than 102,132 years at an assumed 55°C temperature and 60% confidence level. One parameter not included is terrestrial radiation-hardness, which is inherently better than Si due to the wide band-gap of SiC, again giving a useful edge to robustness.

Test Name	Test Standard	# Samples x # Lots	Failures
High Temperature Reverse Bias (HTRB)	MIL-STD-750-1 M1038 Method A (***1000 Hours***) TJ=175°C, V=80% Vmax	77x7 lots	0/539
High Temperature Reverse Bias (HTRB)	MIL-STD-750-1 M1038 Method A (***168 Hours***) TJ=175°C, V=80% Vmax	77x2 lots	0/154
High Temperature Gate Bias (HTGB)	JESD22 A-108 (1000 Hours) TJ=175°C, V=100% Vmax (+25V), bias in on direction	77x7 lots	0/539
High Accelerated Stress Test (HAST)	JESD22 A-110 (96 Hours) TA=130°C/86%RH	77x8 lots	0/616
Intermittent Operating Life (IOL)	MIL-STD-750 Method 1037 DTJ ≥125°C, 3000 cycles (5 minutes on/ 5 minutes off)	77x7 lots	0/539
Temperature Cycle (TC)	JESD22 A-104 (1000 cycles)	77x7 lots	0/539
Autoclave (PCT)	JESD22 A-102 121°C/ RH = 100%, 96 hours, 15psig	77x7 lots	0/539
Parametric Verification	Per Datasheet	100% FT x 9 lots	
Physical Dimensions	Per AEC-Q101 Rev D	30x3 packages	0/90
ESD – Changed Device Model	AEC-Q101-005 Field Induced Charged-Device Model, 3 positive and 3 negative pulses applied to All Pins	10x2 lots	0/20
ESD – Human Body Model	AEC-Q101-001 Human Body Model: R-1500 ohm, C=100 pf, 3 positive and 3 negative pulses applied to All Pins	10x2 lots	0/20
Bondline Thickness	Per Assembly Spec	10x6 lots	0/60
Die Shear	Per Assembly Spec	10x6 lots	0/60
Die Attach Voids	Per Assembly Spec	10x6 lots	0/60
Wire Pull	Per Assembly Spec	10x6 lots	0/60
Wedge Shear	Per Assembly Spec	10x6 lots	0/60
CSAM	Per Assembly Spec	60x6 lots	0/360
Lead Integrity Test	Per AEC-Q101 Rev D	30x2 lots	0/60
Solderability Test	Per AEC-Q101 Rev D	10x2 lots	0/20

Table 1: *Reliability stress test summary – SiC FETs from United SiC.*

The compelling case

Modern AEC-Q qualified wide band-gap devices such as SiC FETs from UnitedSiC are real contenders for the next generation of EV motor drives answering the demand for better performance, overall cost savings and proven, robust operation in this demanding environment. As a result, SiC is expected to dominate the drivetrain in the coming decade.

References:

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[3] https://www.cleanenergyministerial.org/campaign-clean-energy-ministerial/ev3030-campaign
[4] http://unitedsic.com/wp-content/uploads/2016/02/bp_2015_05-Robustness-of-SiC-JFETs.pdf