Beyond the Datasheet: Commercialization of 700 V - 1.7 kV SiC Devices with Exceptional Ruggedness for Automotive & Industrial Applications

Avinash S. Kashyap, Microsemi Corp., USA, avinash.kashyap@microsemi.com
Amaury Gendron-Hansen, Microsemi Corp., USA, amaury.gendronhansen@microsemi.com
Dumitru Sdrulla, Microsemi Corp., USA, dsdrulla@microsemi.com
Bruce Odekirk, Microsemi Corp., USA, bodekirk@microsemi.com
Dennis Meyer, Microsemi Corp., USA, dennis.meyer@microsemi.com
Changsoo Hong, Microsemi Corp., USA, changsoo.hong@microsemi.com
William Brower, Microsemi Corp., USA, william.brower@microsemi.com

Abstract

Wide bandgap adoption in the automotive and industrial markets has reached an inflection point. While the benefits of using silicon carbide devices are well known, industry is currently grappling with issues such as supply, cost/scaling, and risk evaluation of using them in applications that are mission critical and need high ruggedness. This paper will discuss (a) Microsemi's design approach to create widespread adoption of SiC devices through rapid commercialization, and (b) key ruggedness metrics based on industry feedback that is not commonly presented in either datasheets or qualification standards, but can potentially unearth underlying device and package weaknesses undermining reliable long-term operation.

1. High Volume Commercialization: Opportunities & Challenges for SiC

1.1. SiC for Automotive Applications

In the last few years, SiC devices are increasingly being adopted in mainstream applications [1]. Given that the electric vehicle (EV) market has large volume needs, it would be an excellent vehicle to ensure swift large-scale adoption of wide bandgap semiconductors. The recent automotive electrification policy announcements from countries such as China, India, Germany and Sweden are clearly pointing to this trend [2]. However, scaling from low volume needs for specialized applications to high volume automotive has proven to be a challenge in the industry. The economics of SiC at this juncture require 6" wafers in order to be cost competitive with the incumbent Si based system solutions. Since 6" wafer availability is still constrained (due to quality and resource issues), the SiC devices being built need to have high yield. Therefore, the design of the devices need to be optimized such that the yield (esp. related to the gate oxide) stays consistently high even with epitaxy or process variations. This becomes especially important as multiple voltage nodes ranging from 700 V to 1.7 kV start moving into high volume production in rapid succession.

1.2. Design Considerations for the Automotive Market

While the silicon power semiconductor industry had the luxury of gently ramping up and gaining traction in automotive applications, the situation is drastically different for SiC. The prime cause of wide bandgap demand in the auto industry today is due to vehicle electrification – both electric (EVs) and hybrid electric vehicles (HEVs). These vehicles have high power conversion demands that simply cannot be met by existing Si IGBTs and superjunction devices, without trading off on battery size or range. Moreover, the switch to vehicle electrification happened in a relatively short period of time, prior to the commencement of full-fledged SiC high-volume manufacturing in 6" wafers.

The crystal growth of SiC substrates is a slow and expensive process. SiC wafers cost about two orders of magnitude more than their Si counterparts. While the number of defects per wafer has drastically reduced over the years, they are still higher than Si. The inherent yield would therefore be lower than for Si devices. To keep the costs lower for the automotive industry, the design and the process for SiC needs to be tailored towards maximizing yield and performance. This can be achieved by (a) centering the process and providing higher tolerances, thereby preventing process roll-off due to variation, (b) adopting a conservative approach in the device design (for example, reducing the gate oxide stress with a lateral structure, as opposed to a trench FET), (c) providing reliability and ruggedness by design rather than relying solely on testing, and (d) assessing the performance of the devices in non-standard conditions beyond what is provided in the datasheets.

High volume automotive manufacturers prefer to source components from multiple vendors for risk mitigation. A consistent design philosophy for both SBDs and MOSFETs was adopted such that the datasheet parameters would be “average” or well-centered against what is already available in the market. At the same time, Microsemi parts would be differentiated by industry leading reliability and ruggedness. This would enable automobile power electronics engineers to switch an existing designed in part with their Microsemi equivalents even if they were not initially considered, or for future retrofitting needs. An example of this approach is shown in Fig. 1. The center blue hexagon represents the Microsemi SBD vs. the competition. For all major parameters, the Microsemi SBD is in the center of the spider web, ensuring that they can be an easy replacement for an already designed in part.

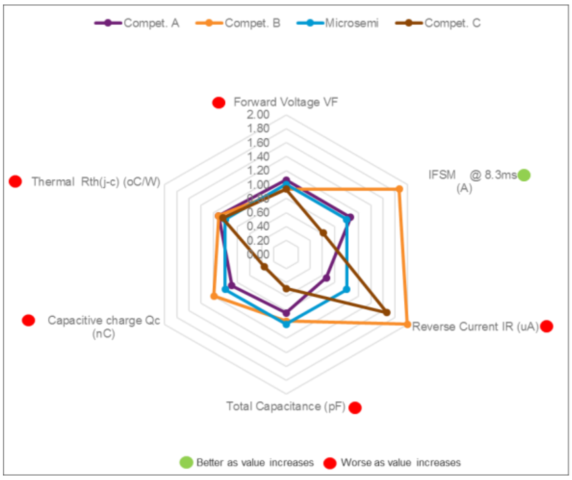

Fig. 1. Spider web comparison of Microsemi 1.2 kV, 10 A SBD vs. the competition.

The same method is also employed for MOSFETs, thereby opening up more choices for high volume customers. The major electrical characteristics of SiC MOSFETs and SBDs and how they were optimized for the auto industry is discussed below in detail.

2. Salient Features of Automotive Grade SiC MOSFETs

2.1. Electrical Performance Criteria

One of the main attractions of using SiC is the energy density the devices provide. This allows a drastic reduction in the number of individual components used in a power module, thereby improving reliability. By using large area dies (Rds,on ~15-25 mΩ), high current modules can be designed with less components. The improvements in gate oxide quality and the reduction in wafer/epi defects have made this possible. Moreover, the on-state resistance of the SiC MOSFETs increased by ~60% (Fig. 2) from 25 °C to 175°C compared to over 200% in Si superjunction devices [3]. For a given use case temperature, this once again translates to deploying less number of dies for the same current

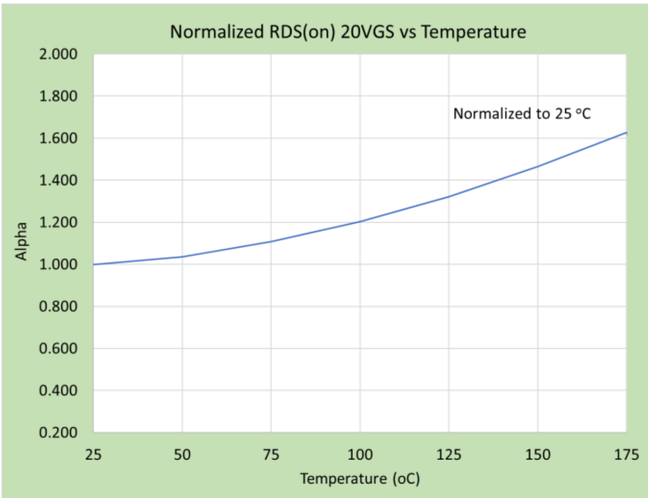

Fig. 2. Rds,on vs. Temperature of Microsemi’s Next Gen 1.2 kV, 40 mΩ SiC MOSFET (MSC040SMA120B).

rating.

From a conduction loss perspective also SiC FETs fare better, as IGBTs have higher losses at low load conditions (idling, slow driving) due to the constant V_{CE} drop across them.

The low losses encountered during high-frequency switching (eg. on-board chargers and DC-DC converters) is another critical feature of SiC devices. The figure of merit (FOM) for these FETs were optimized to provide a low C_{RSS} value, that directly impacts the turn-off time positively and reduces E_{OFF}.

While significant efforts are made to reduce capacitances in SiC MOSFETs, the same in not necessarily true for the ESR or gate resistance. When the device has a high internal gate resistance, the turn-on/off is slowed down and the switching losses increase considerably. Discrete SiC MOSFETs targeting the auto industry need to have a low internal gate resistance to utilize the full benefits that wide bandgap offers. Microsemi has

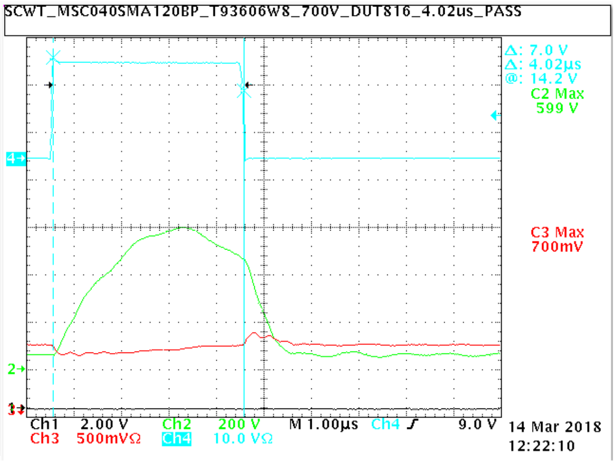

Fig. 3. MSC040SMA120B part demonstrating an SCWT of >4 µs at 700 V.

incorporated this into the design resulting in MOSFETs with ESR of <1.5 Ω. The end user might incorporate external gate resistors to suppress oscillations/EMI. Having a low ESR allows greater flexibility in choosing the resistor values based on the design needs.

Another important device parameter is the short circuit withstand time (SCWT). It can be defined as

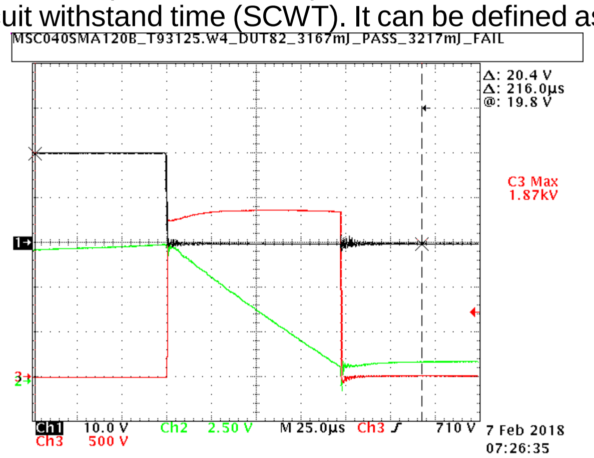

Fig. 4. MSC040SMA120B MOSFET passing a single-shot UIS test at 3 J.

the maximum time under a rail-to-rail short condition for the device to fail. Some manufacturers opine that having an intelligent gate drive system can preclude a catastrophic event and therefore, an SCWT rating is not necessary. However, for critical power electronic systems such as those used in EVs, significant safety margins need to be built into the system and putting the onus on the gate drive for protection would not be sufficient. While SiC MOSFETs may not match IGBTs in this parameter, having a 3-5 µs SCWT rating would provide an adequate safety margin for automobile applications (Fig. 3).

The significance of having avalanche capability (Fig. 4) for power devices is well known [4]. Given that high performance power electronic systems are highly optimized, even a minor malfunction by a passive could result in transient voltage spikes that can exceed the rated voltage. If the device is not rated for unclamped inductive switching (UIS), then one or more transient voltage spikes could easily kill the device and possibly the entire system, a risk against reliable long-term operation.

2.2. Reliability

Over the last several years, the reliability of SiC parts have steadily improved to a point, where they can be safely equated to their Si counterparts [5-6]. The quality of the gate oxide process and improvement of the SiC-SiO_2 interface is one of the major reasons for achieving the high reliability seen today. Results of TDDB and lifetime tests performed by Microsemi (and other vendors) have shown millions of hours of lifetime for the gate oxide, clearly indicating that extrinsic failures are no longer a limiting factor for SiC MOSFETs. Issues such as bias threshold instability (BTI), body diode degradation and material (substrate/epi) induced failures are no longer a concern for reliable operation. The AEC-Q101 qualification standard widely used for Si power semiconductors has been adapted for SiC by various manufacturers. End users of SiC devices gain tremendous confidence in the devices when they pass this qualification as it is one of the most stringent standards available today. Other industries requiring high reliability such as Aerospace have also started requesting AEC-Q101 qualified parts for their applications. For modules, qualification standards such LV324 help validate the reliability of the technology.

To ensure the long-term reliability of the gate oxide, performing high dv/dt (>100 V/ns) switching tests for hundreds of hours is necessary. If there are any weak spots in the oxide itself or the shielding, then high dv/dt tests could expose those effectively.

As many power electronics applications demand 3rd quadrant operation, the body diode of the SiC MOSFET need to be stressed under DC bias conditions for at least 1000 hours to prove that they are not affected by bipolar degradation. It is recommended that the rated MOSFET current under the maximum allowable junction temperature is made to flow through the body diode during this test. Fig. 5 shows the results for body diode DC stress.

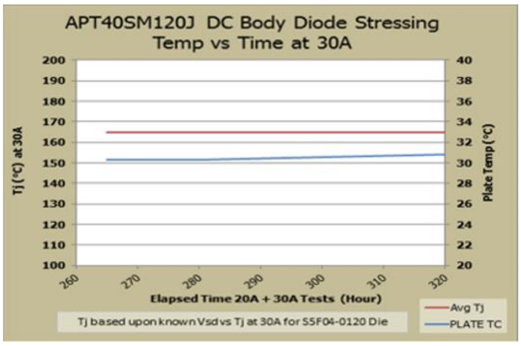

Fig. 5. Results of body diode DC stress of 1.2 kV SiC FETs.

3. Ruggedness Requirements for the Auto Industry

3.1. Introduction

While several publications have pointed to the excellent reliability of wide bandgap MOSFETs and diodes [7], there is still a small lingering hesitation from the automotive and industrial markets because of the absence of field data. The typical reliability metrics to demonstrate the stability of SiC devices have been high temperature reverse bias (HTRB), high temperature gate bias (HTGB), time dependent dielectric breakdown (TDDB), temperature cycling, etc. With these tests, industry has shown that problems such as negative bias threshold instability (NBTI) and gate oxide integrity/lifetimes are no longer stumbling blocks for SiC usage in mainstream power electronics. The widespread acceptance of the stringent AEC-Q101 & LV324 standards to qualify SiC devices and modules in recent times has also helped further the cause. The prevailing sentiment is that because the AEC-Q101 is a high bar and a necessary automotive standard, passing it should be sufficient for industrial applications and the EV market. While datasheet characterization and AEC qualification sheds substantial light on the long-term reliability of the devices, it is not adequate to conclusively establish their ruggedness. Automotive and industrial circuits can be electrically noisy being exposed to various internal and external transients. While it is possible to engineer around that by overdesign, one would be sacrificing performance at the altar of safety, and crimping the engineers' design space. In some instances, the trade-off can be so drastic that from a cost perspective, SiC would not be effective any more.

Based on internal observations and industry feedback, the following metrics are considered critical from a ruggedness perspective: unclamped inductive switching (UIS) rating, repetitive UIS (R-UIS) analysis, repetitive surge current hits and mission based power cycling. The performance of SiC diodes and MOSFETs (700 V, 1.2 kV and 1.7 kV) is discussed in detail for some the tests outlined above.

3.2. Design for Ruggedness

For both SBDs and MOSFETs, the main design aspect imposed for every voltage node was forcing

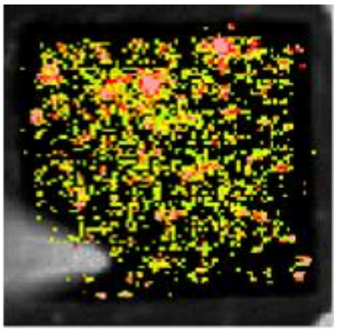

Fig. 6. Backside emission imaging of the SiC SBD at the onset of avalanche showing uniform breakdown in the active area.

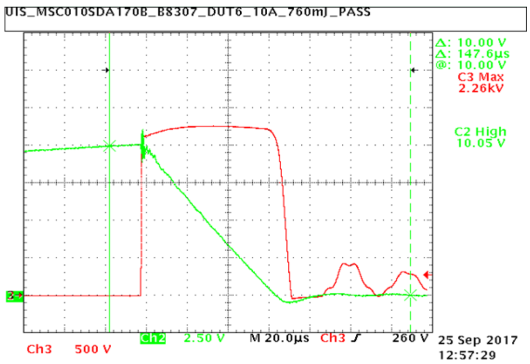

Fig. 7. Successful UIS test performed on 1.7 kV SiC SBD with an energy rating of 760 mJ.

avalanche in the active area and not in the high voltage termination of the device (Fig. 6). This was made possible by designing from the ground up with the UIS capability in mind and using a validated TCAD based approach. The similarity of SiC SBDs (MPS) [8] and the structure of the p-wells of the DMOS allowed for a common design methodology. Additional UIS layers were placed in the active area of the DMOS design [9], with the clear goal of suppressing the turn on of the parasitic NPN bipolar of the SiC MOSFET under the most stressful electric field and current conditions. The SBDs and MOSFETs were designed to have UIS ratings between 10-15 J/cm^2, based on their breakdown voltages (Fig 7). By designing a high voltage termination with a breakdown voltage (BV) higher than the active area, the avalanche process is forced in the active area, thereby eliminating what could be a potential weak spot under high voltage stress conditions.

3.3. Repetitive UIS Test

While repetitive UIS is not yet a standard test for SiC, from a practical usage standpoint, it offers more information on the ruggedness of the device than one-shot UIS tests. For the R-UIS test, 1.2 kV, 10 A diodes were subjected to repetitive pulses at 48.5 Hz with inductors ranging from 0.4 mH to 2 mH, ramping up the R-UIS energies up to 100 mJ,

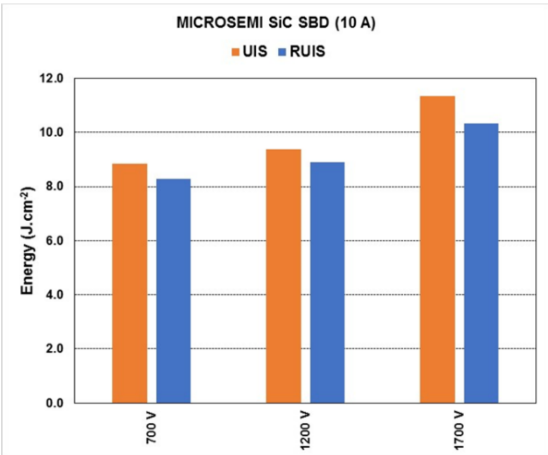

Fig. 8. Comparison of energy levels (fail points) of single shot UIS vs. repetitive UIS for 700 V, 1.2 kV and 1.7 kV SBDs.

which is the rated single shot UIS energy for the device.

The parts were mounted on a heatsink and placed under a fan to minimize self-heating. The tests were also repeated with the 700 V and 1.7 kV SBDs. As expected, the ruggedness increases with the voltage rating (about 22% increase in energy from 700 V to 1.7 kV, Fig. 8). The fail points

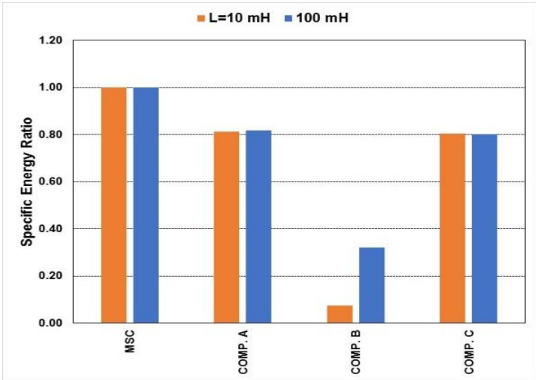

Fig. 9. Benchmarking of UIS performance of Microsemi SBDs vs. the competition.

were noted for single shot vs. R-UIS tests. The energy levels were ~5% lower for the 1.2 kV and 9% lower for the 1.7 kV SBDs.

Multiple diodes were subjected to this test, and as seen in Table 1 (shown for one of the DUTs), the VF of the device remains unchanged from the rated (and pre-test) value of 1.5 V after 10,000 sequential hits. To the best knowledge of the authors, this is the first reported study of this kind.

Table. 1. Results of R-UIS test performed on 1.2 kV/10 A SiC SBDs with no change in performance after 10 K hits.

DUT94 Amps	ENERGY (mJ)	INDUCTOR (mH)	VR (V) 100μA	VR (V) 1mA	IR (nA) 1200V	VF (V) 10A
Pre Reading			*1500*	*1530*	*156*	*1.50*
10	20	0.4	1490	1520	157	1.50
10	40	0.8	1490	1520	157	1.50
10	60	1.2	1490	1520	160	1.50
10	80	1.6	1490	1520	163	1.50
10	100	2.0	1500	1530	162	1.50

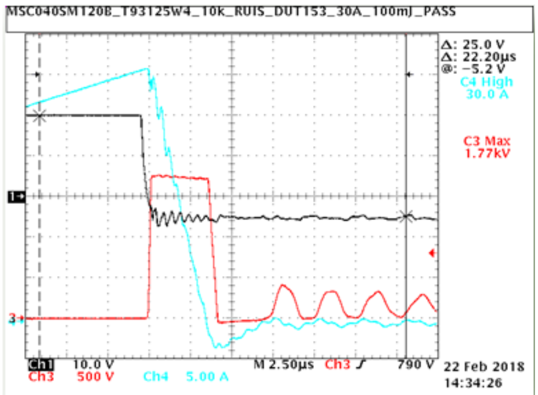

Fig. 10. MSC040SMA120B MOSFET passing 10K UIS hits at 100 mJ.

Table 2. Results of repetitive UIS test performed on MSC040SMA120B MOSFETs with no change in performance after 10K hits.

	P/F	Pre IDSS (A)	Post IDSS (A)	Pre RDS(on) (Ω)	Post RDS(on) (Ω)	Pre IGSS+ (A)	Post IGSS+ (A)	Pre IGSS- (A)	Post IGSS- (A)	Pre VSD (V)	Post VSD (V)	Pre VGS(th) (V)	Post VGS(th) (V)
DUT152	PASS	1.13E-07	1.10E-07	33.6	33.1	4.70E-11	1.30E-09	-2.90E-11	-2.90E-11	-3.68	-3.67	2.33	2.33
DUT153	PASS	8.00E-09	8.00E-09	34.6	34.0	3.30E-11	1.10E-09	-2.10E-11	-2.10E-11	-3.71	-3.69	2.54	2.53
DUT161	PASS	8.70E-09	8.70E-09	34.1	33.8	5.30E-11	1.00E-09	-2.90E-11	-3.00E-11	-3.73	-3.72	2.47	2.52
DUT162	PASS	1.80E-08	1.80E-08	34.2	33.9	6.70E-11	7.04E-10	-4.00E-11	-4.00E-11	-3.71	-3.71	2.44	2.43

The repetitive UIS tests were then performed on the MSC040SMA120B MOSFETs to validate the performance of the high ruggedness design. Fig. 10 shows the waveforms of the10,000th UIS hit. Table 2 presents the electrical data for several MOSFETs post the repetitive UIS tests, confirming minimal or no change in leakage current, threshold voltage, Rds,on and body diode performance.

This test clearly demonstrates the robustness of the gate oxide under extremely stressful conditions imposed on the parts repeatedly.

3.4. Repetitive Surge Current Tests

In certain automotive applications, the SiC devices may be subjected to repeated surge current conditions. While the I_{frm} rating of diodes provide some indication of the capability to withstand repeated surges, it would be most beneficial to get experimental validation of the same. Microsemi's 1.2 kV/20 A SiC SBDs were subject to 1000 back-to-back surge hits at 60% of the 8.3 ms half-sine wave single hit rating. Due to the repeated current surges, this test thermally stresses both the packaging and the die. Fig. 11 shows the nearly invariant leakage current and VF after the 1000 hits stress on the SBDs. This test is also planned to be performed on the body diodes of SiC MOSFETs in the future.

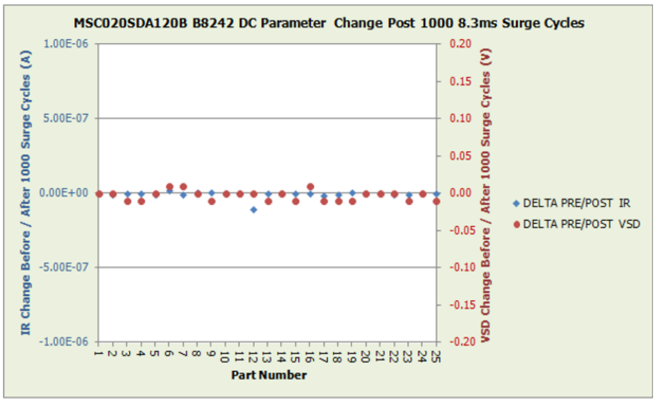

Fig. 11. Leakage current and VF values pre- and post-1000 hits stress on SiC SBDs.

4. Summary & Conclusions

Given the imminent scale-up of the SiC market, the discussions and data presented in this paper are expected to be invaluable to the automotive and industrial market decision makers.

The automotive industry is at a turning point with respect to electrification, and SiC is poised to help in that effort significantly. Given the short-term challenges related to substrate availability and high-volume scale-up, a manufacturing strategy that involves high yielding designs and process becomes indispensable to address speedy ramping needs and supply chain concerns.

Currently, ruggedness tests such as the ones outlined in this paper are not standardized or presented in datasheets. Going beyond what is merely "sufficient" resonates strongly with the automotive industry as it grapples with the introduction of new technology that essentially acts as the engine for EVs.

Acknowledgement

The authors would like to thank the US Department of Energy and the PowerAmerica Institute for funding part of this work via subaward #2014-0654-22.

5. References

1. X. She, A. Q. Huang, O. Lucia, B. Ozpineci, "Review of Silicon Carbide Power Devices and Their Applications," *IEEE Trans. Industrial Electronics*, vol. 64, no. 10, pp. 8193-8205, Oct. 2017.
2. "Electric cars are set to arrive far more speedily than anticipated," *The Economist*, Feb. 2017.
3. Datasheet of IPD60R170CFD7 superjunction MOSFET.
4. K. Fischer, K. Shenai, "Dynamics of power MOSFET switching under unclamped inductive

loading conditions," *IEEE Trans. Electron Devices*, Vol. 43, Issue 6, June 1996.

5. S. Buetow, R. Herzer, G. Koenigsmann, M. Rossberg, A. Maul, "High power, high frequency SiC-MOSFET system with outstanding performance, power density and reliability," *International Symposium on Power Semiconductor Devices and IC's (ISPSD)*, Sapporo, 2017.
6. P. A. Losee, A. Bolotnikov, L. C. Yu, G. Dunne D. Esler, J. Erlbaum et al, "SiC MOSFET design considerations for reliable high voltage operation," *IEEE International Reliability Physics Symposium (IRPS)*, Monterey, CA, 2017.
7. J. Palmour, "Silicon carbide power device development for industrial markets," *IEEE International Electron Devices Meeting*, San Francisco, CA, 2014, pp. 1.1.1-1.1.8.
8. A. Gendron-Hansen, D. Sdrulla, B. Odekirk, A. S. Kashyap, L. Starr, "4H-SiC 1200 V Junction Barrier Schottky Diodes with High Avalanche Ruggedness," *Int. Conf on SiC and Related Materials (ICSCRM)*, Washington DC, 2017.
9. I. H. Ji, A. Gendron-Hansen, M. Lee, E. Maxwell, B. Odekirk, D. Sdrulla, C. Hong, A. S. Kashyap, F. Faheem, "Highly rugged 1200 V 80 mohm 4-H SiC power MOSFET," *International Symposium on Power Semiconductor Devices and IC's (ISPSD)*, Sapporo, 2017, pp. 371-374.