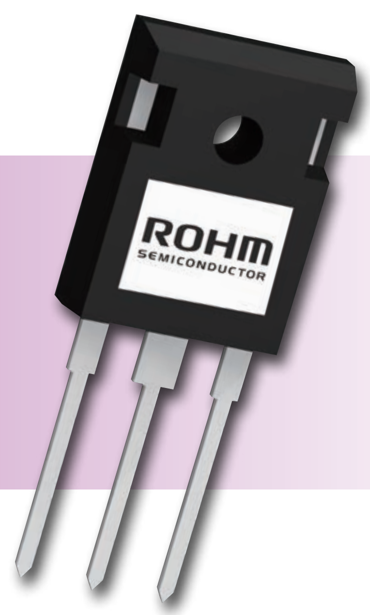
Innovations Embedded

The Next Generation of Power Conversion Systems Enabled by SiC Power Devices



White Paper

The world has benefitted from technology innovations and continued advancements that have contributed to highly integrated and robust power systems. But all this power can have a downside in the form of higher energy costs and the negative environmental side effects of producing and consuming an increasing amount of energy to run these products. This has prompted a global effort to make all systems "greener" with the implementation of more strict regulations and standards, but has also encouraged new markets and applications development.

For instance, the technology used in today's electric and hybrid vehicles successfully convert more than 85 percent of the power into usable energy, which is double a gasoline engine's efficiency. However, a higher goal for these vehicles has been set by the U.S. Department of Energy (DOE), which calls for these vehicles to convert 93 percent of their power into energy by 2015 and squeeze out another 1 percent to a total of 94 percent by 2020. On top of these challenging objectives, the DOE has also set the target that electric traction drives, which are responsible for the energy conversion, need to be half the size and less than a fifth of the cost of what they are currently by 2020.

In addition, many states have adopted aggressive renewable energy goals mandating that a growing percentage of electricity come from clean energy sources such as solar. According to the Union of Concerned Scientists (UCS), several trends have emerged in the past couple of years regarding state renewable energy standards. The UCS cites "an increasing number of states are adopting higher targets, while many states with existing standards have increased or accelerated their targets. Sixteen states (plus D.C.) now have requirements of 20 percent or more. In addition, more state standards include provisions specifically designed to support solar and/or small-scale renewable energy systems".

Therefore, the three main drivers of the development of next-generation power semiconductor devices are regulatory rules, which call for higher efficiency in power conversion systems; market demands for improved, lighter, smaller, more cost-effective systems and emerging new applications such as electric vehicles (EVs) and solid state transformers (SSTs). Up until recently silicon has been the main material used in power electronics, and although silicon technology continues to improve, it does present certain limitations in continuing to meet the growing demands placed on power conversion systems.

Work in the past decade has shown that wide bandgap (WBG) materials such as Silicon Carbide (SiC) and gallium nitride (GaN) can serve as the foundation of the next-generation of power semiconductor devices. The advances in WBG power devices deliver dramatic improvements in performance as well as new capabilities, which are not possible with silicon-based devices. Only recently, however, have WBG power devices, those based on SiC in particular, been considered part of the tool kit of power system designers. This is due to a confluence of factors; namely the availability of all components needed to build complete power systems (SiC diodes, switches and modules), an expanded supply chain and suppliers offering more economically viable pricing. Since GaN power devices have just begun to be offered commercially, these solutions are still in their infancy. For that reason, this paper will focus on the latest type of SiC device, the MOSFET. It will present SiC device characteristics and what benefits this breakthrough technology delivers for power systems.

History of SiC-based Products

The first commercial SiC Schottky Barrier Diodes (SBDs) were introduced more than ten years ago. Since then, SiC SBDs have been designed into many power systems, most notably into power factor correction (PFC) circuits of switch mode power supplies. These were followed by SiC power switches – JFET, BJT, and MOSFET. For applications that require higher power levels than can be supported by discrete devices, suppliers are now providing power modules, which integrate multiple discrete devices (packaged or bare die) into compact form factors. These compact form factor modules are available in all-SiC or hybrid IGBT-SiC SBD versions.

There are multiple SiC SBD suppliers. The first SiC switches offered are JFET and BJT, and SiC MOSFETs are the most recent addition in the last two to three years. Technology maturity, performance and dramatic cost reduction due to increasing volume and competition are the main reasons SiC MOSFETs have been adopted in more and more applications.

SiC SBDs are currently available with breakdown voltage ratings of 600V-1700V and 1A-60A current ratings. Thus, SiC devices tend to compete with silicon MOSFETs in the 600V-900V range and with IGBTs in the 1kV+ range. Generally both packaged parts and bare die are available.

Successfully integrated into power systems for more than 10 years, the benefits of SiC SBDs are well known to power engineers. The most recent entrant, SiC MOSFETs, are increasingly popular with power designers due to the device's normally-off operation, that it is a voltage controlled device and the simplicity of its gate drive compared to junction gate field-effect transistors (JFETs) and bipolar junction transistors (BJTs). ROHM Semiconductor recently announced the release of two new 1200V SiC MOSFETs, designated SCT2080KE and SCH2080KE, that are designed to deliver cost-effective, breakthrough performance. Both are 80-milliohm (mΩ) devices, and the ROHM SCH2080KE is the industry's first SiC MOSFET co-packaged with a discrete anti-parallel SiC Schottky Barrier Diode (SBD). The characteristics, advantages, device parameters, and measurements will be provided in this paper as examples.

SiC MOSFET - Leveraging SiC's Material Properties to Improve Power Switches

An ideal power switch has the following characteristics:

- Able to carry large current with zero voltage drop in the on-state
- Blocks high voltage with zero leakage in the off-state
- Incurs zero energy loss when switching from off- to on-state and vice versa

With silicon, it is difficult to combine these desirable but diametrically opposed characteristics, especially at high voltage and current. For example, at breakdown voltage 800V and higher, the channel resistance (and hence forward voltage drop) is very high because of the large drift region required to withstand such voltage. Insulated Gate Bipolar Transistor (IGBT) devices were developed to address this problem. With IGBTs, low resistance at high breakdown voltage is achieved at the cost of switching performance. Minority carriers are injected into the drift region to reduce conduction (on-) resistance. When the transistor is turned off, it takes time for these carriers to recombine and "dissipate" from the base region, thus increasing switching loss and time.

A quick review of material properties explains why power devices made with SiC can outperform their silicon counterparts. Figure 1 lists key electrical and thermal properties of Si and some WBG materials.

Properties	Si	4H-SiC	GaAs	GaN
Crystal Structure	Diamond	Hexagonal	Zincblende	Hexagonal
Energy Gap : E_G (eV)	1.12	3.26	1.43	3.5
Electron Mobility : μ_n (cm^2/Vs)	1400	900	8500	1250
Hole Mobility : μ_p (cm^2/Vs)	600	100	400	200
Breakdown Field : E_B (V/cm) $X10^6$	0.3	3	0.4	3
Thermal Conductivity (W/cm°C)	1.5	4.9	0.5	1.3
Saturation Drift Velocity : v_s (cm/s) $X10^7$	1	2.7	2	2.7
Relative Dielectric Constamt : ε_S	11.8	9.7	12.8	9.5
p, n Control	○	○	○	△
Thermal Oxide	○	○	×	×

Figure 1: Physical Characteristics of major wide bandgap materials

SiC MOSFET Switching Performance/Benefits

Thanks to SiC's breakdown field strength that is ten times higher than that of silicon, SiC devices can be constructed to withstand the same breakdown with a much smaller drift region. In theory, SiC can reduce the resistance per unit area of the drift layer to 1/300 compared to silicon at the same breakdown voltage.

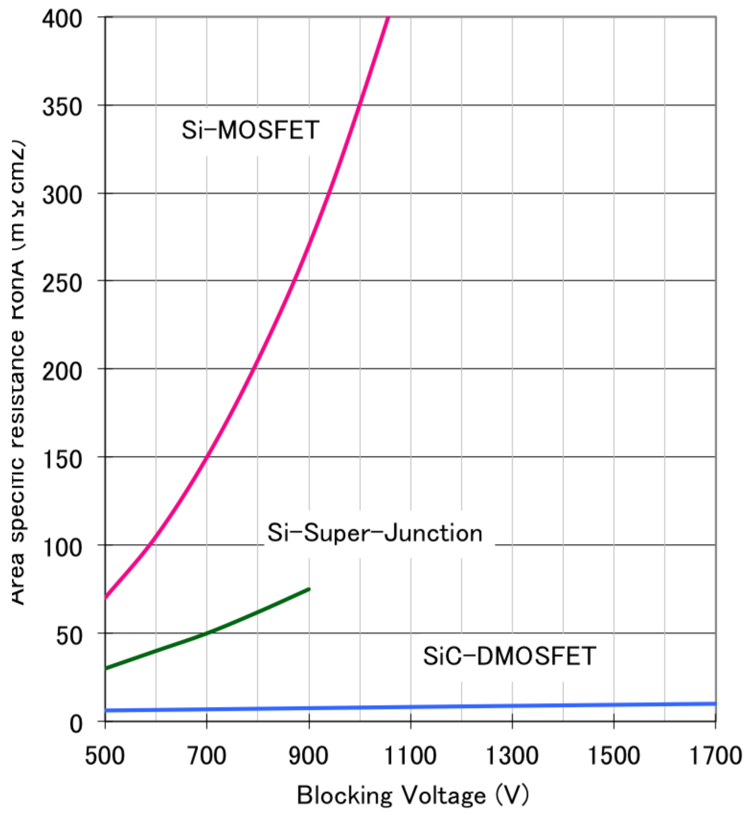


Figure 2: Comparison of Specific On-Resistance of Si-MOSFET and SiC-MOSFET

MOSFETs are majority carrier devices so they have no "tail" current, as is the case with IGBTs when turned off. SiC MOSFETs, therefore, combine all three desirable characteristics of power switch, i.e., high breakdown voltage, low on-resistance and fast switching speed. As an example, ROHM's SCT2080KE SiC MOSFET features a breakdown voltage of 1200V, 80mΩ on resistance, and turn-on / turn-off time of less than 70-90 ns, enabling switching frequency in hundreds of kHz range. Newer devices with up to 50% lower on-resistance are planned by ROHM.

SiC MOSFET's smaller die size means smaller parasitic capacitances. Compared to a silicon 900V MOSFET, Ciss and Coss are 10 times smaller. At 100 nC, the gate charge is approximately five times smaller.

SiC MOSFET's superior switching performance is shown in Figure 3 and Figure 4. Compared with silicon IGBTs and fast recovery diodes (FRDs), ROHM's SCH2080KE, which combines SiC MOSFET and SiC SBD in one package, exhibits 88% lower turn-off loss and 34% lower turn-on loss. The improvement in turn-off is due to absence of tail current in the MOSFET. The improvement in turn-on is due to the much lower recovery loss of the SiC diode.

The tests below were conducted at Vdd = 400V, Icc = 20A, and 25˚C, and diode recovery losses are included.

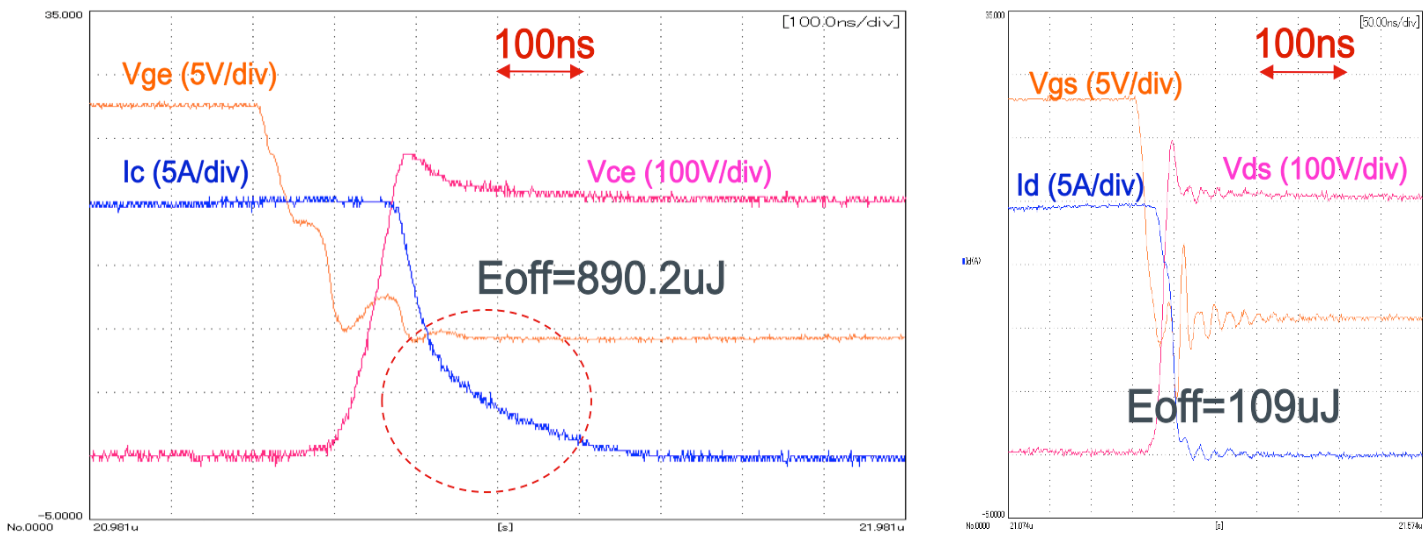


Figure 3: 88% Reduction of Turn-off Loss: SiC-MOSFET + SiC SBD vs. Si IGBT + FRD

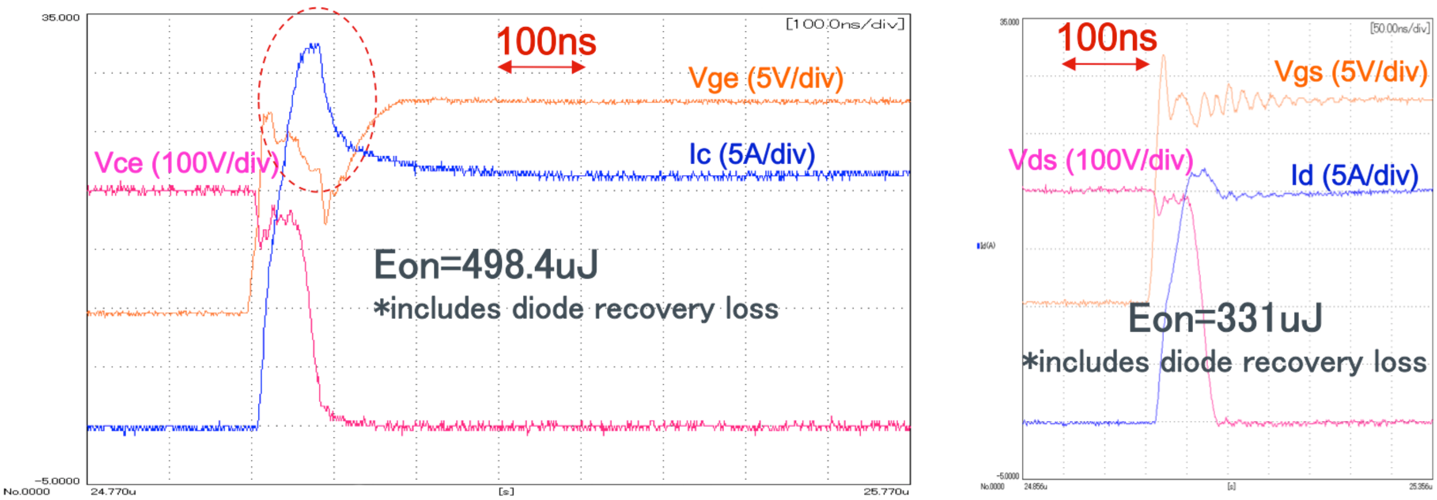


Figure 4: 34% Reduction of Turn-on Loss: SiC-MOSFET + SiC SBD vs. Si IGBT + FRD

Such low switching losses bring a couple of significant benefits:

- Low losses equates to less heat generation, which translates into simpler, cheaper, smaller, and/or lighter cooling systems and ultimately higher power density.
- Low switching losses allows switching frequency to increase to reduce sizes of passive components (capacitors, inductors), reducing system cost, size, and weight. The size reduction is roughly proportional to the increase in frequency.
- Less heat allows lower operating temperature, thus components do not have be derated as much, allowing perhaps smaller, less expensive components to be used. At the system level, this means a lower-rated SiC system can replace higher-rated silicon system.

Figure 5 below illustrates these two points. It shows that at 20 kHz switching frequency, a 100-A SiC half bridge module that is forced-air cooled can replace a 200-A IGBT module that is water cooled.

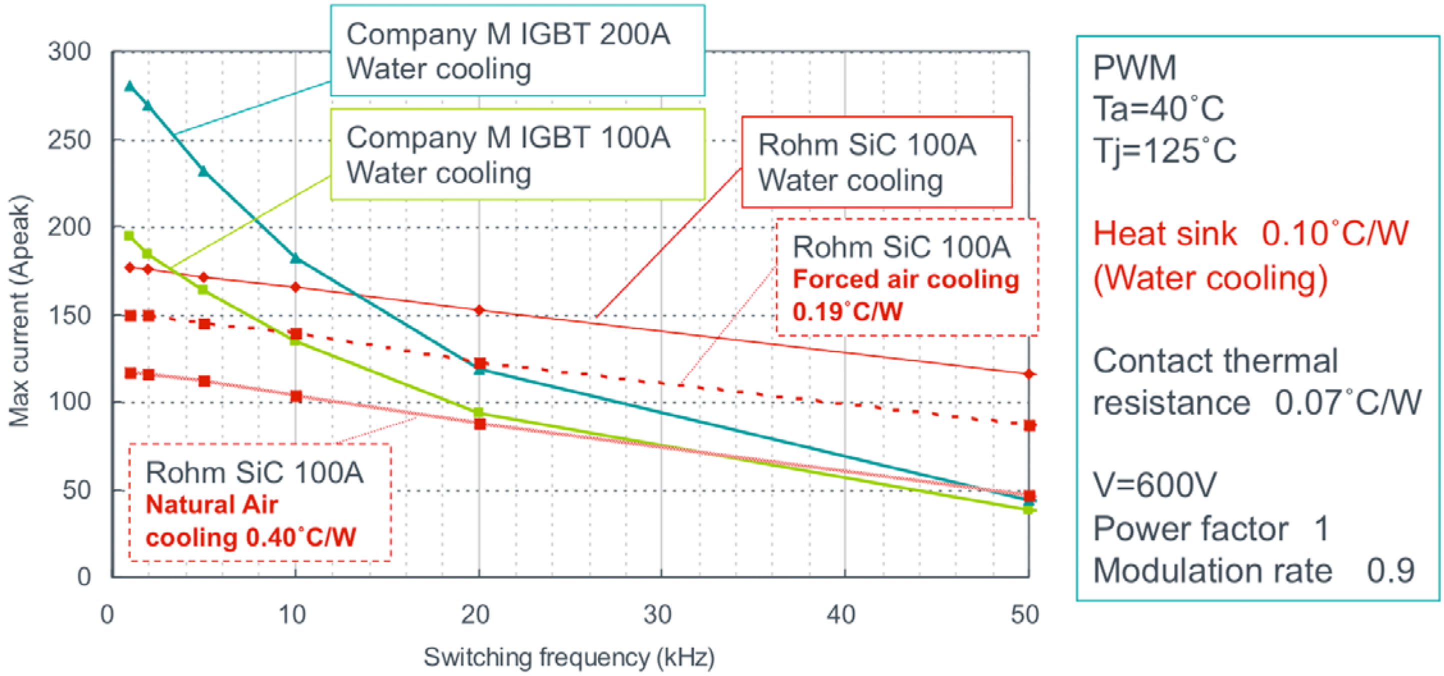


Figure 5: Lower switching losses allow 100A SiC Module to replace 200A IGBT Module

SiC MOSFET's Fast Body Diode

Unlike silicon MOSFET's, the body diode of a SiC MOSFET excellent reverse recovery performance, which is comparable to that of discrete SiC SBD. Figure 6 shows that the reverse recovery waveform of the ROHM SCT2080KE SiC MOSFET's body diode is virtually identically to that of the ROHM SCH2080KE, which comprises SCT2080 MOSFET die co-packed with a discrete SiC SBD. The only meaningful difference between the two diodes is in forward voltage drop. Vf of the body diode is 4.6V; that of the discrete diode, 1.3V.

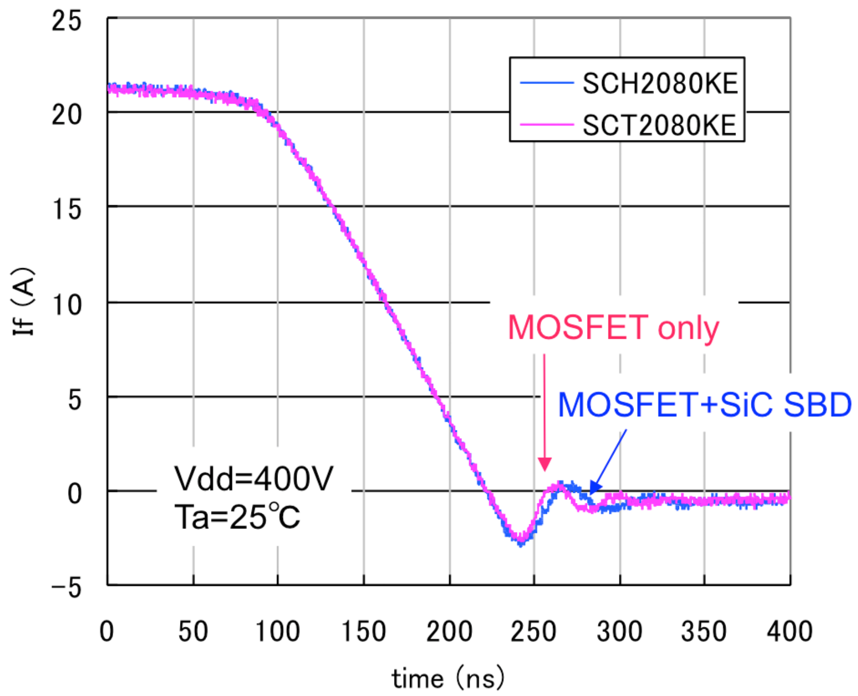


Figure 6. SiC MOSFET's body diode recovery performance vs. discrets SiC SBD

SiC MOSFET High Temperature Advantages

Because of the material's larger bandgap, a SiC device can operate at very high temperature. Currently available SiC SBDs and MOSFETs are rated only at 150˚C to 175˚C, mainly due to packaging limitations. SiC power modules that use special die bonding technology have been demonstrated to work at 250˚C. And there is R&D work in progress where these devices have been proven to operate at 650˚C. The upper limit of silicon semiconductor device is 300˚C, when the material ceases to behave as semiconductor.

Additionally, SiC's thermal conductivity is three times higher than that of silicon. These properties contribute to lower cooling needs, making it simpler to cool SiC components. This results in supporting thermal systems that can be smaller, lighter and lower cost.

In addition, the electrical characteristics of SiC MOSFETs do not vary with temperature as much as silicon MOSFET (this is true for SiC SBD as well). For example, the Rds-on of ROHM's SCT2080KE is 80 mΩ at Tj = 25˚C. At Tj = 125˚C, Rds is 125 mΩ, which is a 56% increase. With silicon MOSFETs, the increase is more than 200%. The benefit is that SiC MOSFETs do not have to be derated to the same extent as silicon.

The high temperature capabilities of SiC power devices have not been fully exploited because of limitation of today's packaging technology and the associated lower operating temperatures of other components in systems.

SiC MOSFET Reliability

Reliability is a one of the most important considerations in power electronics design, whether the application is grid conversion power conversion or electric drives in EV or home appliances. Therefore, because SiC is a new material, frequently one of the very first questions about SiC devices from power system engineers is: "Is it as reliable as silicon?" We will present three of the most important aspects related to overall reliability: gate oxide reliability, stability of gate threshold voltage Vth, and the robustness of the body diode with reverse conduction.

A common failure mode of MOS devices is electrical overstressing of the gate oxide. Gate oxide quality, therefore, directly affects SiC MOSFET's reliability. Developing high-quality oxide on SiC substrate has been a challenging problem for the industry until recently. The goal is to minimize defect density – interface and bulk traps – so as not to compromise lifetime and electrical characteristics stability.

Figure 7 shows the result of Constant Current Stress Time-Dependent Dielectric Breakdown (CCS TDDB), which is a standard test that measures the quality of gate oxide MOS. The accumulated charge QBD is a quality indicator of the gate oxide layer. The value of 15 - 20C/cm2 is equivalent to that of Si-MOSFETs.

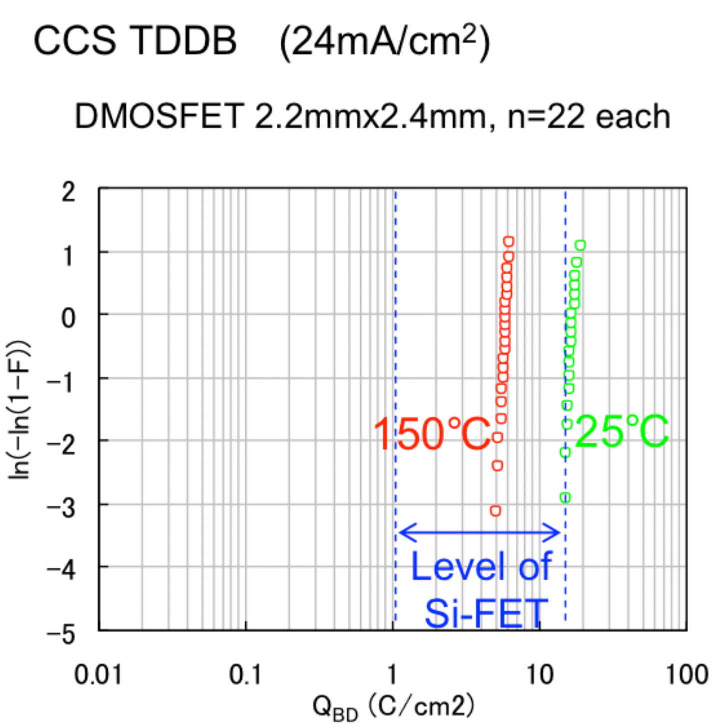


Figure 7. Constant Current - Time Dependent Dielectric Breakdown Measurements

Another aspect of device reliability is the stability of the gate threshold voltage Vth as the gate is subjected to positive and negative biases. When a positive voltage is applied to the gate for an extended period of time, crystal defects at the oxide-SiC interface trap electrons and cause Vth to increase as shown in 8. Similarly, when a negative voltage is applied, trapped holes cause Vth to decrease as shown in 9. The tests are performed on ROHM's SCT2080KE. The shift in Vth is 0.3V or less.

This is comparable to that of a silicon MOSFET. In practical usage, the shift would be much smaller since MOSFETs are alternately switched on and off. This allows trapped electrons and holes to "escape" between switching cycle. Hence the accumulated trapped carriers, which cause shift in Vth, are much less.

HTGB (+22V, 150° C)

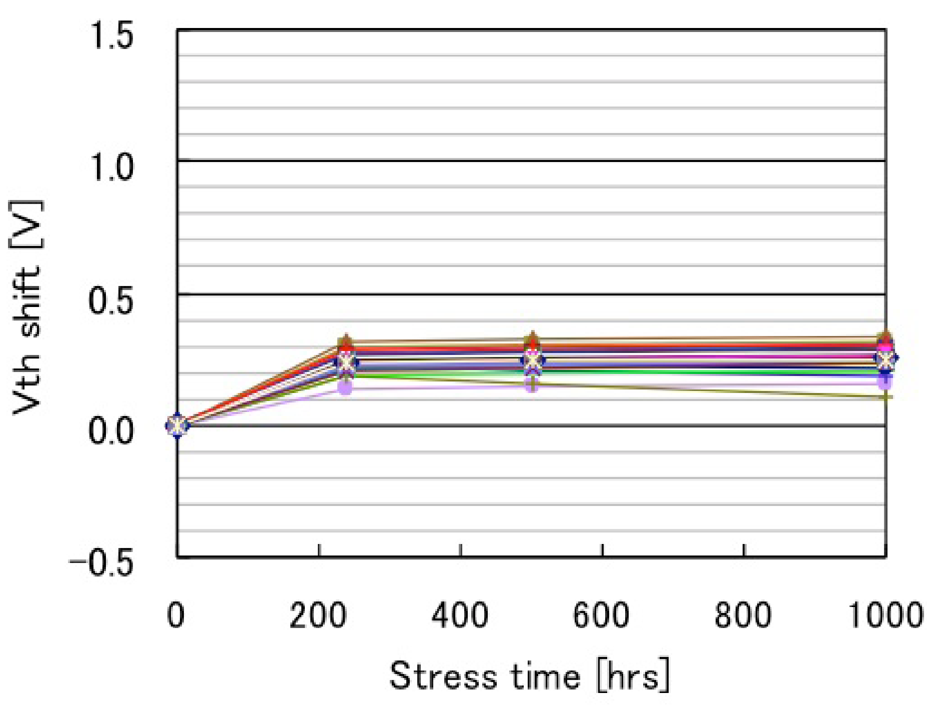


Figure 8. Vth increases due to extended application of positive gate voltage

HTGB (-6V, 150° C)

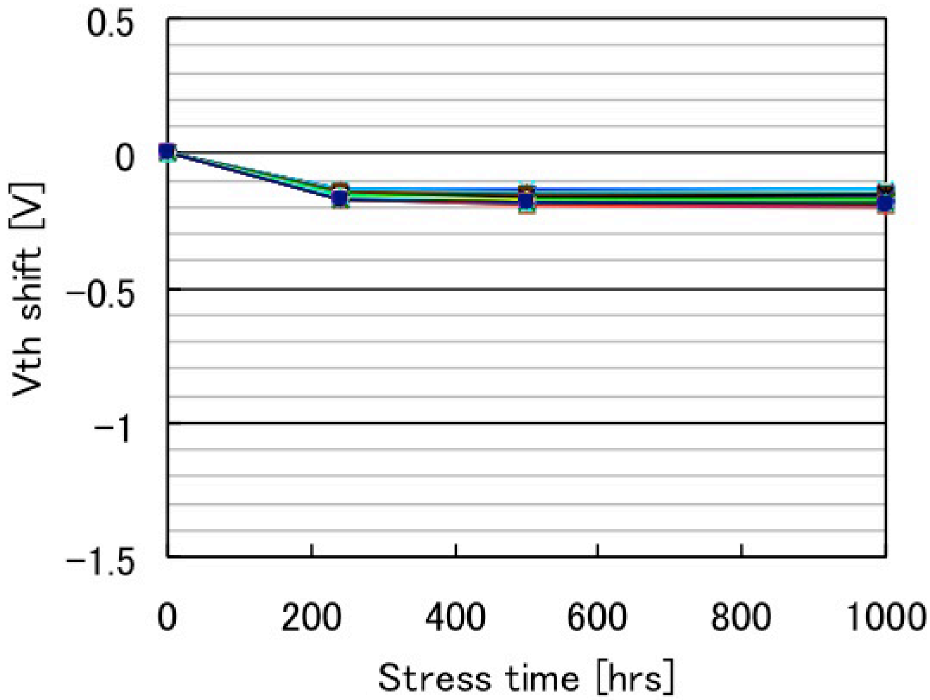


Figure 9. Vth decreases due to extended application of negative gate voltage

SiC MOSFETs with reliable body diodes allow them to be used in circuit topologies that cause commutation to the body diode, e.g., bridge topologies in inverters. If not controlled, defects in wafer and epi layer causes on-resistance, the diode's forward voltage drop and leakage current to increase as forward current flows through the diode. This is due to the propagation of stacking faults caused by recombination energy. Local heating increases with on resistance, which then induces more faults.

ROHM has developed a proprietary process to minimize defect density as well as the propagation of faults. Test results on the ROHM SiC MOSFET SCT2080KE show that the body diode is robust under reverse conduction (see Figure 10).

Body-diode conduction test (If=8A DC, Ta=25°C, 1000h)
DUT:SCT2080KE (TO247 w/o SiC SBD)

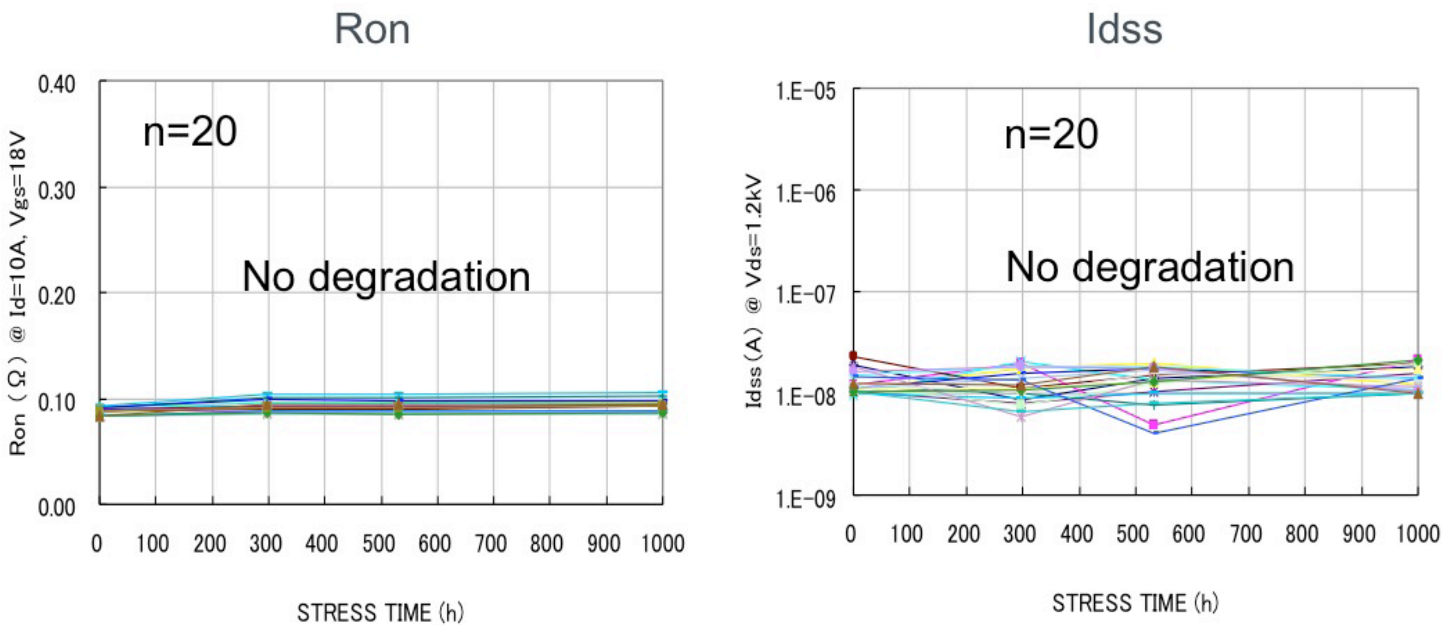


Figure 10. Body Diode Conduction Test

Working with SiC MOSFETs

SiC MOSFETs have been proven to be easy to work with because they are voltage controlled devices and are driven similarly to the way silicon MOSFETs and IGBTs are driven.

However, there are some differences worth noting:

- The gate voltage swing is from -6V to 22V. The nominal values are 0V-18V. This is larger than 15V for IGBT. 18V is the minimum needed to achieve rated 80 mΩ on-resistance. The higher gate voltage is to "compensate" for the lower carrier mobility in SiC. Driving the gate below -6V would cause a large shift in Vth.
- Since the body diode has reverse recovery performance comparable to that of a discrete SiC SBD, there might not be a need for external anti-parallel diode unless the use case demands it. Similarly, the series diode to prevent conduction through the body diode might not be needed, further saving cost.

- Since ROHM's SiC MOSFETs have very robust body diodes, they can be used as bidirectional switches. When used this way, the large forward voltage drop of the body diode is bypassed, i.e., the voltage drop is that of the source-drain resistance, which is dependent on Vgs. Figure 11 details this behavior.

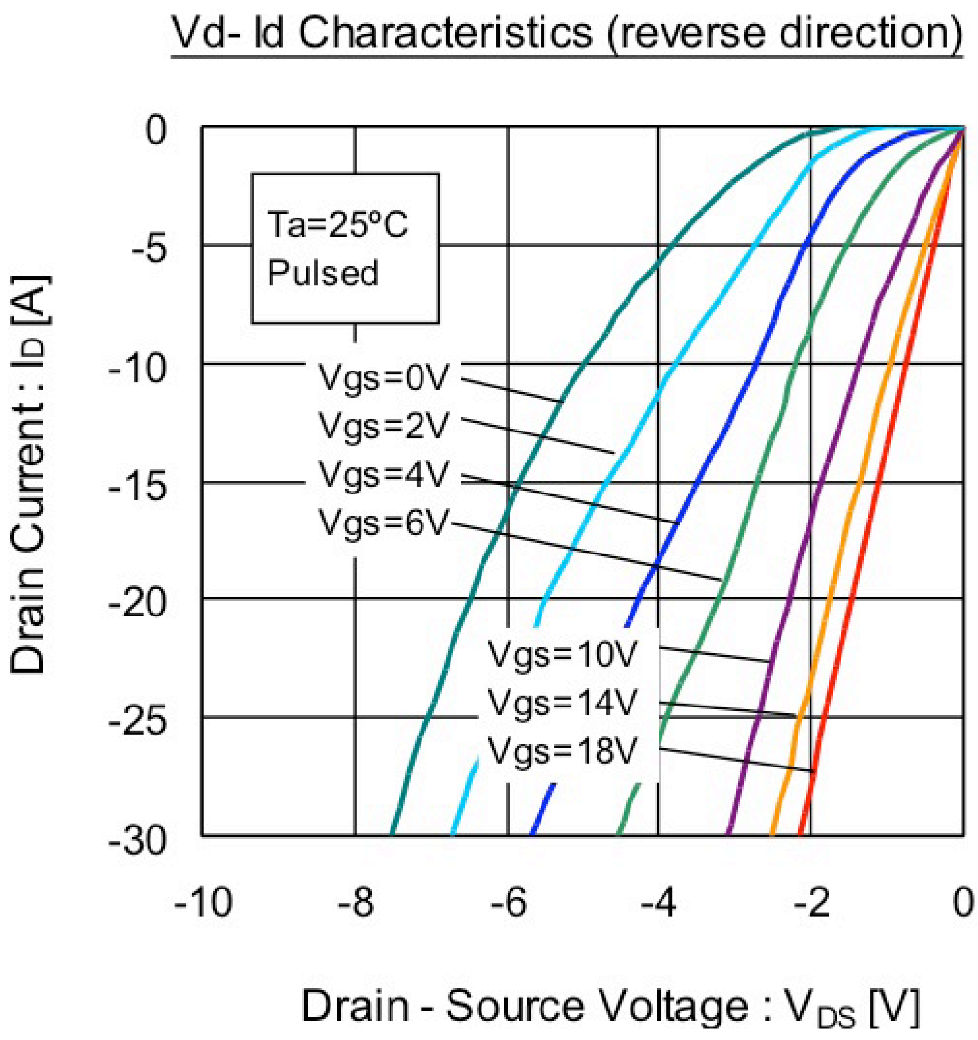


Figure 11. Id vs. V_{DS} During Reverse Condition

ROHM SiC MOSFET Portfolio and Roadmap

ROHM Semiconductor offers an extensive lineup of SiC MOSFETs, covering breakdown voltage from 400V to 1700V and current rating from 10A to 63A. Devices are available in through-hole packages as well as bare die.

The first two members of Rohm's SiC MOSFET product line, SCT2080KE and SCH2080KE, have been in mass production since July 2013. Both are 1200V, 80-mΩ devices. SCH2080KE contains SCT2080KE die and discrete anti-parallel SiC SBD diode in the same package. This saves board space, simplifies layout, and costs less than equivalent discrete parts. A first in the industry, SCH2080 is especially suited to applications in which small size and weight are important, e.g., motor drives and dc-dc conversion in aerospace and EV/HEV. Other members of the 1200V family include smaller, lower cost MOSFETs with Rds-on ranging from 160 mΩ to 450 mΩ as well as larger die (higher current rating) and Rds-on that is almost ½ that of current devices. All of these devices are already qualified for 175°C.

Although the advantages of SiC MOSFETs tend to be more pronounced at high breakdown voltage, 1000V and higher, they can also offer superior value in 400-650V power conversion systems that require combination of high speed switching and low on-resistance that silicon MOSFETs and IGBTs cannot provide.

In the near future, ROHM has plans to offer an exciting next-generation of MOSFET - the trench MOSFET. The main advantage of this vertical architecture is its extremely low on resistance, thanks to the elimination of the JFET resistance inherent in the planar architecture and much higher channel mobility. Specific on-resistance of less than 1.25 mΩ cm2 has been achieved for the 1200V device. Smaller die size mean trench MOSFETs will also cost less. These two characteristics allows switches with very high current rating - 60A or larger – to be cost effectively manufactured. This, in turn, enables the development of more cost-efficient SiC power modules that can handle very high current, e.g., 600A – 1 kA. Such modules are not economically feasible today as they require a significantly larger number of individual die.

Enabling Enhanced Power Conversion System Applications

Though there have been many great advances in technology in the last decade, and the supply chain continues to expand, the industry is still at the dawn of the wide bandgap technology era. As the industry pushes forward to fully leverage and realize the SiC's full potential, the next generation of SiC power devices is well-positioned to enable new high-volume applications such as EVs and solid state transformers. Enhancing these applications will continue to stimulate market demand while acting as the driver for future technology development. It is ROHM's commitment to further advancements in SiC power device technology that will give system designers the promise of even more exciting developments in the decade to come.

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