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Reliable SiC Power Devices for Automotive Applications

Power devices are a key elements in electric and hybrid electric vehicles. As one of the technology leaders in SiC power devices Rohm has been supplying electric vehicle manufacturers with SiC power devices since 2012.

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The mission of Rohm is to produce power devices that meet high reliability standards at all times. This philosophy has enabled Rohm to increase the SiC business in the automotive field with a steadily growing demand and close cooperation with customers. This article focuses on automotive-grade SiC power devices, including some of their common applications and reliability data. In detail, this comprises an overview of SiC MOSFETs and Schottky barrier diodes and their main target applications, e.g. battery charging systems and power train inverters. Special focus is put on the qualification process of our devices including experimental results from reliability tests, such as gate oxide reliability, cosmic radiation ruggedness and SiC MOSFET's body diode bipolar degradation effect.

The prospects for electric vehicles (EV) have greatly improved, turning electric mobility into a subject of significant interest. Car manufacturers, industrial companies and research institutes have joined forces in order to push forward the planned mass production of hybrid and electric vehicles. In doing so, newly developed power electronic systems are also being integrated into EVs. Due to the special requirements demanded by automotive OEMs, system developers are confronted with new challenges. The required space, weight and efficiency play an important role. Furthermore, the overall system cost and the expenses should remain low, while at the same time top-quality and reliability need to be guaranteed for the products.

For a successful integration of EVs into the mobility landscape, technological barriers need to be overcome with concepts that are able to push the barriers away from the current limitations. There is a general consensus among automotive manufacturers that the standard approach does not always achieve performance targets for EVs or meet all design restrictions. The autonomy range of a car is a direct reflection of the power train efficiency and energy management system. On the other hand, public infrastructure systems such as high-power fast charging systems of several hundreds of kilowatt have to operate under tight size and efficiency restrictions. The semiconductor material SiC and its physical properties seem to have all the potential needed to fulfill these new market demands.

Rohm is a market leader in SiC-based power devices whose cooperation with automotive manufacturers dates back to 2012, with the inclusion of SiC Schottky Barrier Diodes (SiC SBDs) in battery charging systems. This has only been possible by offering high reliability and quality standards. In last years, the increasing demand in the automotive market segment has lead Rohm to shift the focus towards this market, aiming to fulfill the requirements of this particular industry in every aspect. It is clear that new technologies do not only bring improvements, but also many questions. Topics such as reliability and quality are as important as the performance benefits obtained by them. At Rohm we are aware of this and do our best to offer a good balance between performance, technological innovation and quality.

This article gives an overview of our automotive-grade power device portfolio, which consists of SiC MOSFETs and SiC SBDs. The first section of this article is focused on the application of our devices as well as new market trends. The other section is dedicated to a selection of experimental results related to SiC MOSFET reliability.

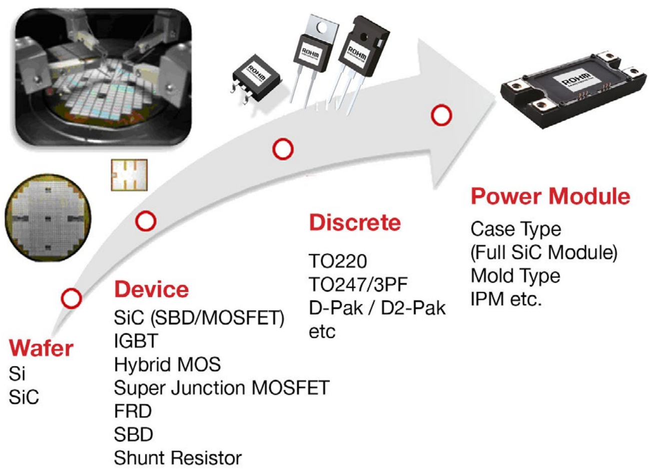

Figure 1: Rohm's in-house integrated manufacturing system for power devices

Rohm's in-house power device development

The high quality standards in our SiC power devices can be assured by our in-house integrated manufacturing system, where every aspect of the device manufacturing is under our control, see Figure 1. This starts as early as at the SiC substrate production, where high quality wafers are produced out of raw silicon and carbon powder. The substrate is a key element for the device quality as some failure mechanisms are directly related to material defects present in low quality wafers. This production step is carried out in Germany by our subsidiary SiCrystal, market leader in SiC substrate manufacturing. The high-quality substrate wafers enable the fabrication of reliable and innovative power devices which is the core of Rohm's contribution to the development of SiC power semiconductor technology. This has been proven by the successful introduction of SiC planar and trench MOSFETs back in 2010 and 2015, respectively. The power devices are sold in a second step as either bare die product, or packaged as discrete devices or in power modules. The discrete devices can be found in through-hole technology (THT) or as surface-mounted devices (SMDs), the power modules are offered in industry-standard C and E type formats. Our full control of the device manufacturing process, quality controls and traceability system allows us to identify and correct possible issues that might arise in any phase of the production chain.

Automotive-grade SiC power devices

Components used in automotive applications have to comply with higher qualification standards than for industrial applications. In the case of power devices the standard AEC-Q101 describes the stress tests that discrete semiconductors need to pass in order to claim automotive-grade qualification. Rohm's product portfolio of SiC SBDs and MOSFETs that comply with this standard is summarized in Table 1.

Device type	Part no.	Voltage	Current / Rds,on	Package
SBD	SCS2xxAJ	650 V	6-20 A	TO-263AB
SBD	SCS2xxAG	650 V	6-20 A	TO-220AC
SBD	SCS2xxAE2	650 V	20-40 A	TO-247
SBD	SCS2xxKG	1200 V	5-20 A	TO-220AC
SBD	SCS2xxKE2	1200 V	10-40 A	TO-247
MOSFET	SCT2xxxKE	1200 V	80-450 mΩ	TO-247

Table 1: Automotive-grade SiC power devices in Rohm's portfolio, after AEC-Q101

SiC SBDs are available in different packages and current ratings, for voltages of 650V and 1200V. They belong to the second generation which features a very low forward voltage and leakage current, and are used in automotive applications since 2012. SiC MOSFETs are available for the 1200V voltage class in planar technology (2nd gen.) and TO-247 housing. The new trench devices (3rd gen.) are currently in qualification process.

EV applications for power devices

Conductive charging

As stated in Figure 2, the first use of SiC devices in automotive applications is related to the SiC SBD in conductive battery chargers, also known as on-board chargers (OBC). They are intended to offer a simple solution to charge the car with a standard household connection and are thus limited to 3.6kW in single-phase and 11kW in three-phase ac input configuration (mode 1 after IEC 62196). A conventional single-phase 3.6kW OBC can be built as shown in Figure 3. The two-stage PFC is composed in this case of a diode-bridge rectifier and a boost converter. The isolated dc/dc converter is commonly realized with a full-bridge converter on the primary side of the transformer and a diode bridge on the secondary side. To achieve an optimum efficiency in the PFC stage, 650V SiC SBDs are already applied as boost diodes, as Si devices would limit the switching frequency to unwanted levels. As efficiency levels increase, the next stage of development of OBCs includes 650V SiC MOSFETs for the PFC and dc/dc full-bridge switches. The use of 1200V SiC SBDs for the output rectifier is also an attractive solution for batteries operating at high voltage levels. As a reference for coming all-SiC OBCs, the system presented in [1] achieved efficiency levels over 95% using 1200V SiC MOSFETs and SBDs at 3.1kW output power.

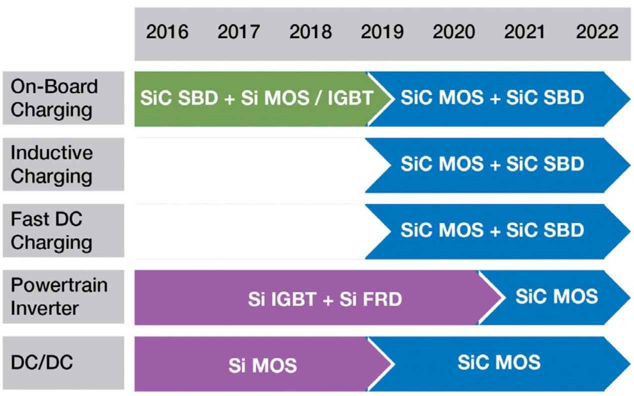

Figure 2: Potential for SiC power devices in automotive applications

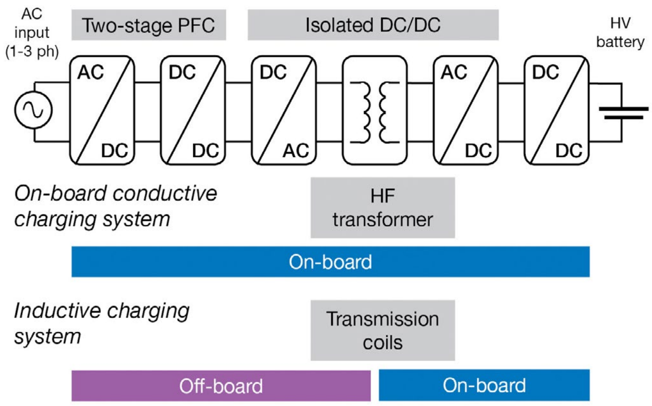

Figure 3: Examples of charging systems for electric vehicles

Wireless charging

Wireless charging for EVs is also an attractive solution for battery charging systems, although the ease of connection translates into a higher system complexity and lower efficiency, see Figure 3. SiC devices can play a key role in these converters, where efficiency (>90%) and 85kHz operating frequency requirements stated in the coming SAE J2954 standard are hard to achieve using standard Si devices. In the optimized design proposed in [2], an efficiency of roughly 94% could be estimated (ac mains to battery) by using 1200V SiC MOSFETs in a 50kW system.

Figure 4: Improvement of perfomance and size reduction in power train inverter with SiC SBD technology for Formula-E racing car

Power train inverter

The power semiconductors used in power train inverters are subjected to high thermal and load cycling. They must exhibit a high short-circuit ruggedness and require a high power rating. The current solutions are mostly based on Si IGBTs as this kind of technology offers a high maturity level and low price. However, benefits of wide bandgap technology on system level, such as reduced volume and higher efficiency, are shifting the interest to SiC MOSFETs as a possible replacement for Si IGBTs in future inverters, see Figure 2. To showcase this trend, Rohm has partnered with the Venturi Formula-E team, where we provide SiC SBDs and MOSFETs for the main traction inverter of a fully electric racing vehicle. The current season features a racing car equipped with Si IGBTs and SiC SBDs, the old Si-based inverter and the new hybrid Si/SiC inverter are shown in Figure 4. For the next season, the IGBTs will be replaced by SiC MOSFETs, enabling even higher efficiency levels and lower volume.

SiC MOSFET reliability

The benefits of SiC technology in power electronic systems are clear, as briefly discussed in the previous section. In order to take advantage of them reliability levels similar to the ones achieved by Si power devices, such as power MOSFETs and IGBTs, need to be achieved. This bears several technological challenges related to new phenomena present in these devices that were unknown in traditional Si technology. The success of power device manufacturers is highly related to the ability to master them and develop stable processes that ensure high reliability at a reasonable price, without neglecting device performance. Rohm power devices are aimed at achieving a good trade-off between performance and reliability which has found a positive response in the market. Our SiC power devices undergo the same tests that standard Si devices require to be qualified for either industrial or automotive use.

Gate oxide reliability

When talking about SiC MOSFETs gate oxide reliability is usually a common concern. Early devices experienced some problems that made many people think that a proper solution would be hard to find. Years of continuous improvement have shown the opposite. Commercially available devices from Rohm feature high gate oxide reliability, with lifetime values far beyond 20 years, as Figures 5 and 6 indicate. Figure 5 shows lifetime plots for 2nd gen. planar and 3rd gen. trench MOSFETs, based on High Temperature Reverse Blocking (HTRB) tests. This test stresses the device with a reverse voltage and high temperature. The electric field that builds up inside the device stresses the gate oxide interface until it fails. This is repeated for many devices and the results are recorded. The lifetime of the device under worst-case operating conditions of 950 V for a 1200 V is obtained by extrapolating the experimental results. This yields a lifetime of over 100 years for both device types.

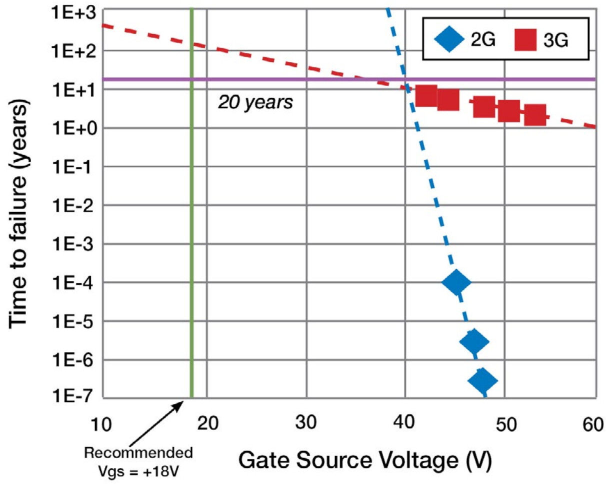

Figure 6: Lifetime calculation of gate oxide based on High Temperature Gate Bias (HTGB) test on 1200V SiC MOSFETs (10 pcs. per each data point, Tj = 175 °C, 70% failure for 2G, 50% failure for 3G)

The other critical condition for the gate oxide is related to the conduction state. In this case the stress is concentrated between the gate and source terminals as a positive voltage is needed to turn on the MOSFET channel. Rohm's MOSFETs have a recommended gate-source voltage of +18V. For the accelerated tests voltages between 40 and 50V were applied. The extrapolation of these results shows that a lifetime of 20 years is obtained with a gate-source voltage higher than 30V. Thus, operation at +18V should not be a concern regarding oxide lifetime.

Cosmic radiation ruggedness

Our planet is under constant cosmic radiation in form of atomic particles that are known to cause failures in power semiconductor devices. Incident neutrons collide with the atomic lattice of the device generating highly localized currents that eventually lead to device failure. This effect is known as Single Event Burn-out (SEB) and can

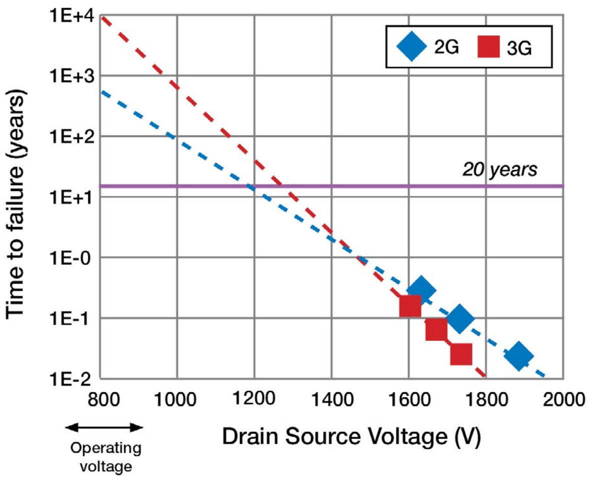

Figure 5: Lifetime calculation based on High Temperature Reverse Bias (HTRB) test on 1200V SiC MOSFETs (10 pcs. per each data point, Tj = 150 °C, 70% failure for 2G, 50% failure for 3G)

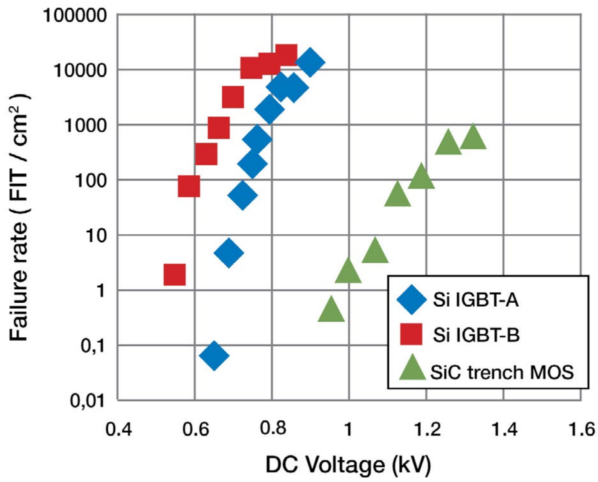

Figure 7: Cosmic radiation induced SEB failure rate of 1200V Si IGBTs and Rohm SiC trench MOSFETs, based on data from [4]

only take place if a voltage over a certain threshold value is applied to the device, usually around 70% of the device breakdown voltage [3]. In traditional Si IGBTs and MOSFETs, the operation voltage is limited to 80% of the device voltage class in order to remain under a rate of 100 FIT. For applications that demand lower failure rate levels, use of devices from a higher voltage class is common. Besides the applied voltage, other parameters that have influence in the failure rate are device area, semiconductor material properties and environmental conditions. Studies performed to assess the cosmic radiation ruggedness of new SiC power devices have been successfully conducted.

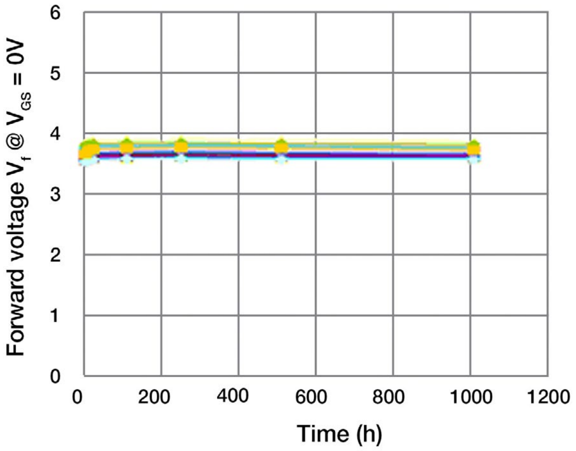

Figure 8: Forward voltage of body diode during DC current stress test (SCT3040KL, IF = 10A, Tj = 175°C, 20 pcs., G-D shorted)

Figure 7 shows results of a test conducted at the ANITA facility in Sweden [4]. This study concluded that SiC trench MOSFETs have a better performance regarding SEB than comparable Si devices. This makes it possible to operate them at higher voltages than Si devices with FIT rates still in reasonable levels. By considering EV battery systems reaching voltage level of 800V in the near future, this is an attractive feature of SiC devices.

Body diode stability

Both crystal defects and the manufacturing process of SiC MOSFETs have a great influence on the stability of the body diode. By acquiring the energy of hole-electron recombination when forward current flows a certain type of a crystal dislocation changes its type from linear to planar shape. This can lead to a degradation of the on-state resistance of the body diode and the MOSFET. Based on its expertise in different manufacturing processes at substrate, epitaxial growth and device level, Rohm’s devices exhibit no bipolar degradation effect. DC current stress tests conducted to 20 planar MOSFETs from Rohm show that these devices do not experience significant degradation even after stressing the body diode with 10A for 1000 hours, as the forward voltage remains constant, see Figure 8.

Avalanche mode capability

Certain applications demand that the power device is able to go into avalanche mode without failure. This is usually caused by overvoltage due to high di/dt and parasitic inductances. For example, an unwanted interruption of the dc charging process using long cables. Other applications demand the connection of power switches to inductive