White paper

Insights into Bosch's silicon carbide (SiC) semiconductor technology

Bosch is one of the leading semiconductor companies for the automotive industry. Bosch offers power semiconductors made of the innovative material silicon carbide (SiC) as bare dies and discretes, as well as integrated in power modules and in comprehensive electrification and mobility solutions. Bosch has more than 20 years of experience with MOSFETs and SiC for the automotive market.

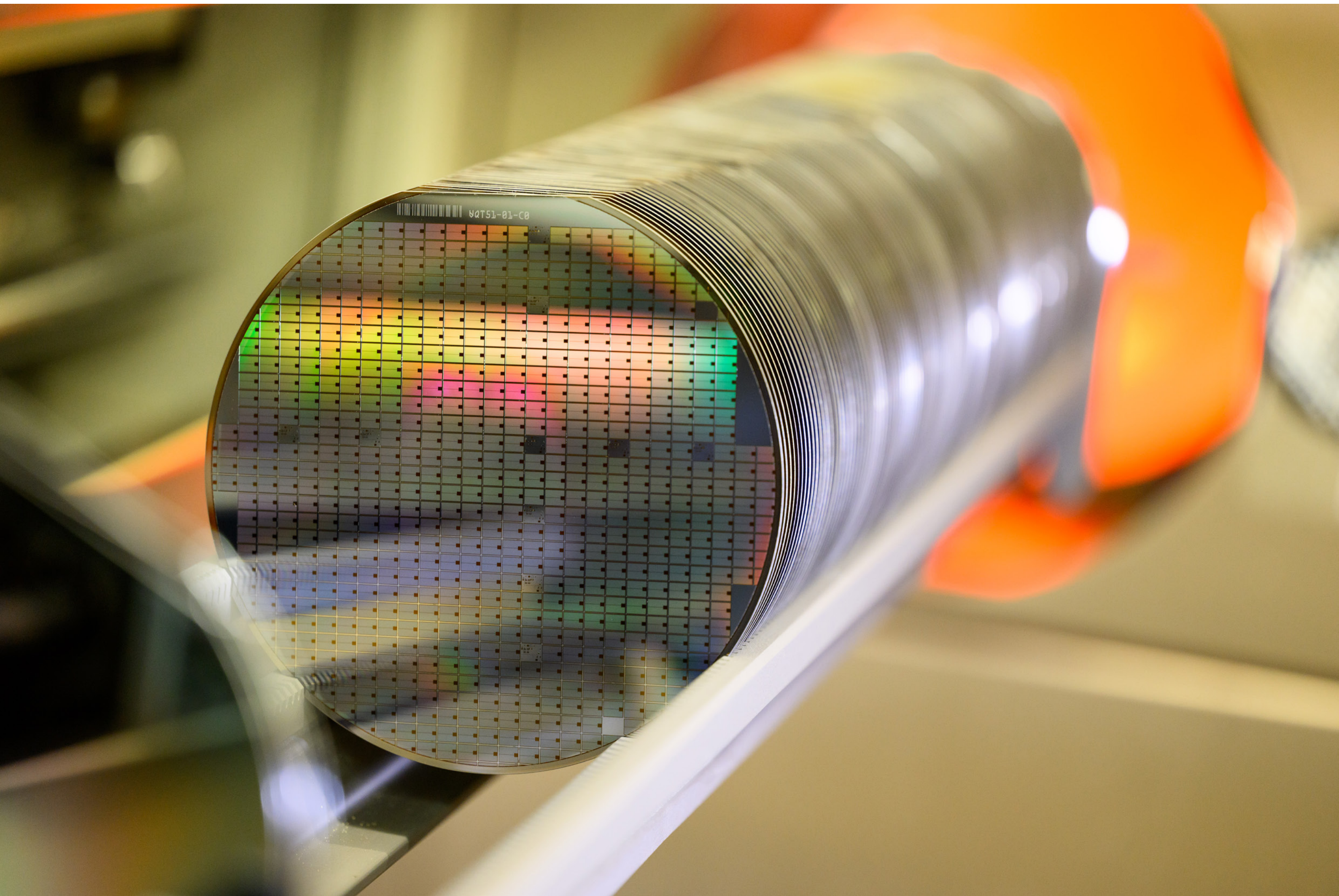
Invented for life

BOSCH

Table of contents

01
Abstract

This white paper explores Bosch‘s silicon carbide (SiC) semiconductor technology for automotive applications. With over 20 years of SiC experience, Bosch offers a comprehensive portfolio, from bare dies to integrated solutions. The white paper covers Bosch‘s dual-channel trench MOSFET technology, substrate innovations, and the transition to 200 mm wafer sizes. It also highlights Bosch‘s global manufacturing capabilities and partner network, emphasizing the company’s commitment to innovation and a secure supply chain for the future of automotive technology.



02
Combination of automotive and semiconductor experience

Like no other company, Bosch combines automotive and semiconductor expertise to develop powerful electronic systems. This in-depth system knowledge in the automotive sector makes it possible to develop customized semiconductors for the respective target application. It enables Bosch to offer innovations in semiconductors and create a competitive advantage through economies of scale in industrialization. With more than 60 years of experience, a global manufacturing and partner network, and sustainable investments in development and production, Bosch is shaping the future of mobility today and is one of the leading semiconductor manufacturers for the automotive industry.

Bosch develops, produces, and markets semiconductors and has positioned itself as an integrated device manufacturer (IDM). By 2035, Bosch expects to have more than 40 of its own chips integrated into each new vehicle.

Bosch develops and manufactures MEMS sensors, integrated circuits, and application-specific integrated circuits and application-specific system-on-chips (AsSoCs). Also, Bosch is one of the few automotive suppliers worldwide that develops and manufactures power semiconductors made of silicon carbide (SiC).

Bosch has more than 20 years of experience in automotive MOSFETs and SiC. The development of SiC semiconductors started in 2001, and the first MOSFET prototype was available in 2011.

Since 2019, Bosch has expanded its presence in the external market and is now also operating as an independent semiconductor supplier: SiC MOSFETs are sold directly to OEMs, Tier 1 and Tier 2 suppliers, as well as distributors in the form of bare dies, discretes, and power modules. The offer ranges from standard solutions to customized SiC semiconductors in special layouts for individual customer projects. This makes Bosch one of the few automotive manufacturers in the world to be so flexibly positioned in the field of semiconductors, and in particular SiC.

Bare die: single, unpackaged chip used in high-performance applications such as power modules for inverters.

Discrete: chip in mold compound package, which is used e.g. in on-board chargers or in DC/DC converters in direct connection with a printed circuit board.

Currently, many OEMs are building up competencies in vertical integration. They are increasingly demanding competitive individual components. Here, Bosch can provide the best possible support with its own semiconductor production and expertise as an automotive supplier. The company draws on many years of experience – for example in the semiconductor process development in production or regarding the requirements for chips for powertrains. Automotive manufacturers who define their E/E architectures themselves benefit from maximum flexibility and the support of a partner at eye level.

Bosch and the Chinese automotive market: strategic partnership for the future

As the world's largest vehicle market, China plays an important role for Bosch, alongside the European home market and the American growth market. The Chinese electromobility market is developing faster than anywhere else in the world and is setting standards in electrification. By 2035, half of the vehicles on Chinese roads will be fully electric. Bosch is already working closely with almost all Chinese automotive manufacturers, as well as with numerous international automotive companies that operate in China. For example, Bosch's SiC chips are widely used in the supply chain of BYD, the world's largest electric vehicle manufacturer, and are prominently featured in high-end vehicle models. Bosch is also a core supplier of SiC products to Great Wall Motors (GWM). In 2022, Bosch signed a long-term SiC supply agreement with XinDong, a joint venture that GWM established with partners. The first Xiaomi car model, the SU7, uses the 400 V eAxle with silicon carbide technology from Bosch at the heart of its electric drive system.

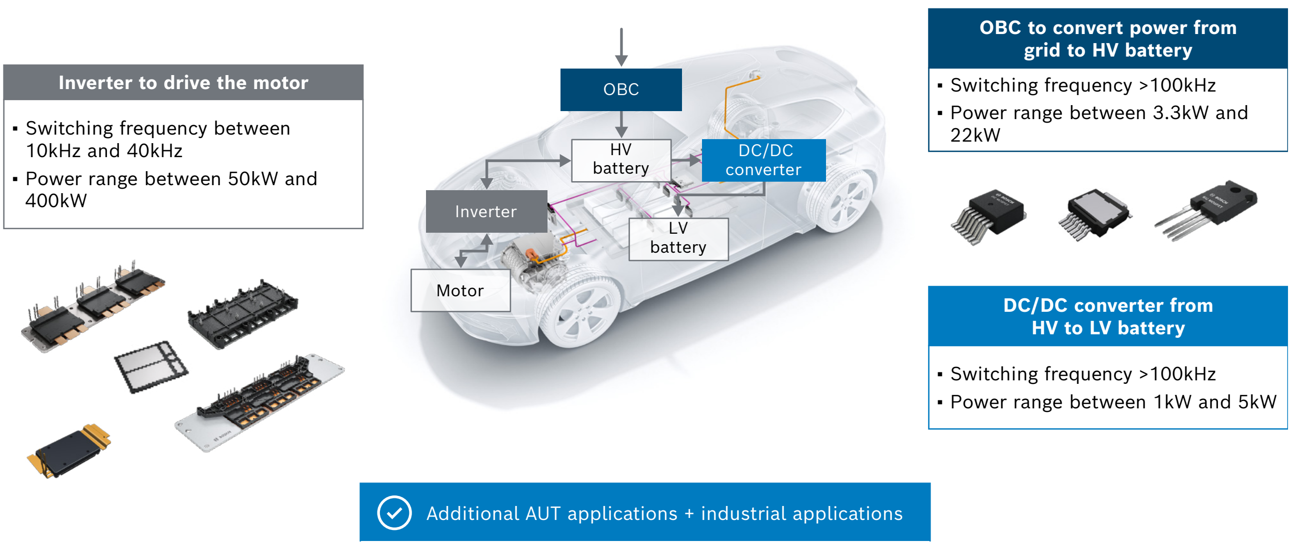


Figure 1: Main SiC automotive applications at a glance.

03
Global manufacturing and partner network

Bosch's strategic focus in terms of locations and global partner network is crucial for production capacities, innovation, and customer proximity, as well as for strengthening supply chain security. This geographic and strategic focus enables Bosch to improve the global availability of semiconductors, drive innovation, and provide faster and more reliable solutions to local markets. Bosch has a strategically designed global network of production and test sites to ensure the highest quality standards and a reliable supply. In addition to the wafer fabs, Bosch also operates test centers. Here, the chips undergo comprehensive testing to ensure their performance, reliability, and compliance with the demanding automotive standards. With this worldwide semiconductor network of front- and backend manufacturing facilities, Bosch is well positioned globally.

Bosch's global semiconductor network is further extended by numerous silicon foundry partners and OSATs (Outsourced Semiconductor Assembly and Test providers). The cooperation with many international partners helps to secure supply chains and improve the global availability of semiconductors.

Bosch has been mass-producing generation 1 of its SiC chips on 150 mm wafers in Reutlingen since the end of 2021.

04
Roadmap and technology

SiC roadmap

The Bosch's SiC technology roadmaps for 750 V and 1,200 V classes support a successful, long-term market placement. Bosch follows a high-paced innovation path by introducing a new generation every 2 to 2.5 years. Each generation features a significant improvement in the key performance indicators compared to the previous one. The power density of the SiC MOSFET increases with each new generation, and switching properties are improved while maintaining or even increasing the level of robustness. In addition to improvements in the cell architecture of the SiC power MOSFETs, new features such as integrated sensing functions or alternative power metallization are also added – always with the goal of providing the highest ease of use and flexibility to Bosch's SiC customers.

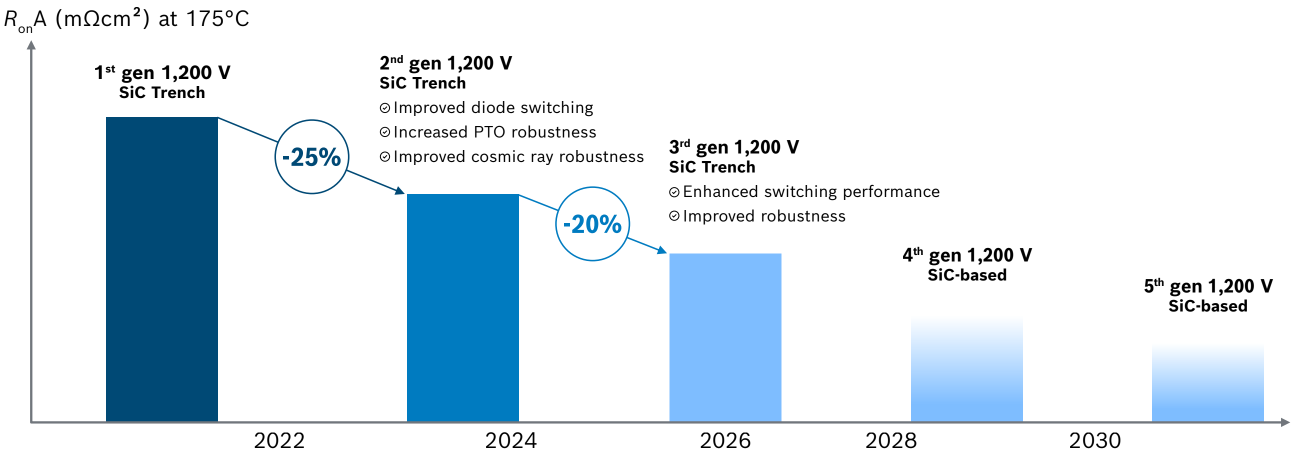


Figure 2: Roadmap for the 1,200 V voltage class.

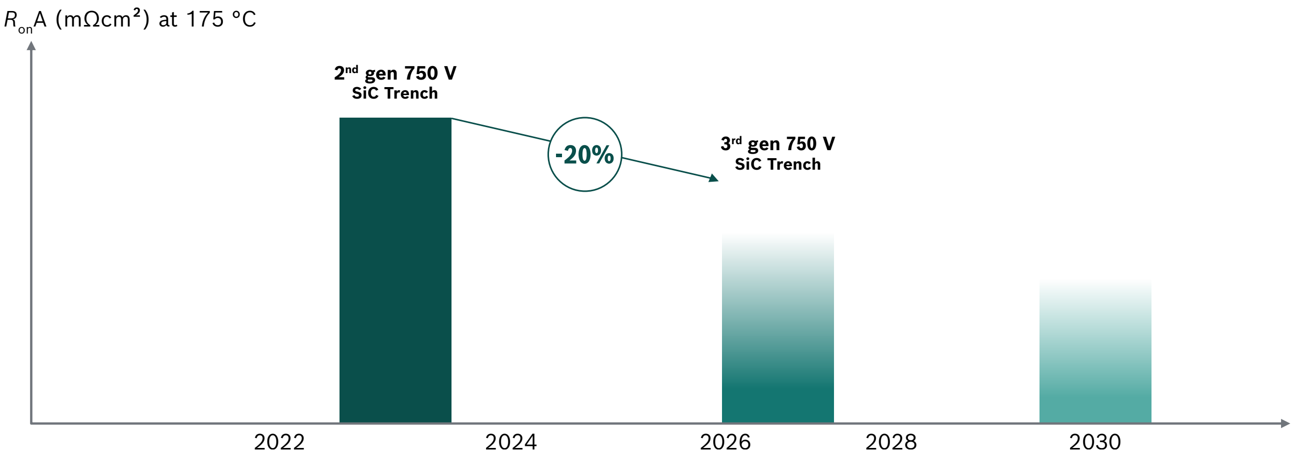
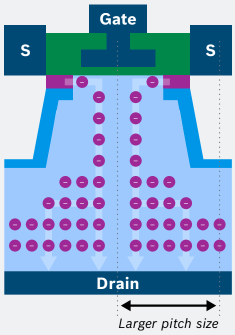


Figure 3: Roadmap for the 750 V voltage class.

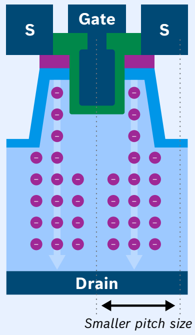
Dual-channel trench concept

Competitors – Planar gate technology



- Used in first and current generations of SiC-MOSFETs
- Larger pitch size → higher $R_{DS(on)}$ x Area compared to trench technology

Bosch – Dual channel trench gate technology



- Bosch's dedicated automotive SiC process
- Bosch's device concept optimized for reliability, e.g., oxide shielding by deep implants
- Dual channel trench technology offers smaller pitch size and lower $R_{DS(on)}$ compared to planar technology, leading to reduced area and cost

The first generation of 1,200 V SiC MOSFET devices from Bosch has one of the best performances on the market regarding $R_{DS(on)}$*A and $R_{DS(on)}$*Qg[1]

1) Source: SiC Transistor Comparison report, Yole Group, 2024

Figure 4: Bosch currently produces high volumes of SiC MOSFETs at its 150 mm wafer fab in Reutlingen. The devices, based on Bosch's proprietary, advanced dual-channel trench gate MOSFET design and manufacturing process, offer advantages over traditional planar gate technology.

Three aspects are essential for modern SiC-MOSFETs in automotive power applications:

- device performance and ruggedness;
- control of SiC substrate quality;
- advanced manufacturing.

Two main structures prevail among SiC MOSFETs: the planar and the trench gate MOSFET. In the planar structure, the gate complex of gate electrode and gate oxide are located at the surface; the current flow in the channel of the transistor is lateral. In contrast, the gate complex in a trench MOSFET is in a vertical trench structure and current flows vertically through the channel. The trench gate enables a significantly smaller unit cell (pitch size) and a decreased area demand of the power chip (increased power density). This is the key advantage of trench architectures compared to their planar counterparts. To drive the trench architecture to maximum performance, Bosch developed a dual-channel trench technology, which allows a unique combination of high static and dynamic performance with enhanced reliability and ruggedness for applications with high lifetime demand. The dual-channel technology uses two electron channels at the sides of every trench. This makes it possible to halve the channel resistance, which is one of the most important fractions of the overall device resistance, compared to single channel architectures.

Dual-channel trench technology for enhanced lifetime and ruggedness

While the performance benefit of SiC trench technologies is undisputed, special care needs to be taken in terms of reliability and robustness. Committed to a zero-defect strategy and reliability-focused design, Bosch ensures safe and stable operation of its SiC power devices over the lifetime of the electric vehicle.

The weak spot of any MOSFET technology is the gate oxide. By using the dual-channel trench technology, the gate oxide can be shielded very efficiently against high electric fields in the off-state of the transistor while simultaneously achieving high reliability in the on-state by carefully controlling the gate oxide process. In consequence, Bosch's dual-channel trench technology pushes the lifetime of the power devices far beyond the typical operating lifetimes, leaving enough headroom to achieve lowest FIT (failure in time) rates. A further focus is on ensuring that the gate oxide used in the SiC MOSFETs from Bosch also has a very low threshold voltage drift. With this minimal shift, switching operation as well as conduction and switching losses remain in the design window of the power module even in applications with very high lifetime demands. The low drift also enables module designs with overall higher performance. Low drift is further ensured when negative gate voltages are used for off-switching as is typically done in traction inverter applications. This demonstrates both the high reliability of the gate oxide and the clear focus on automotive applications.

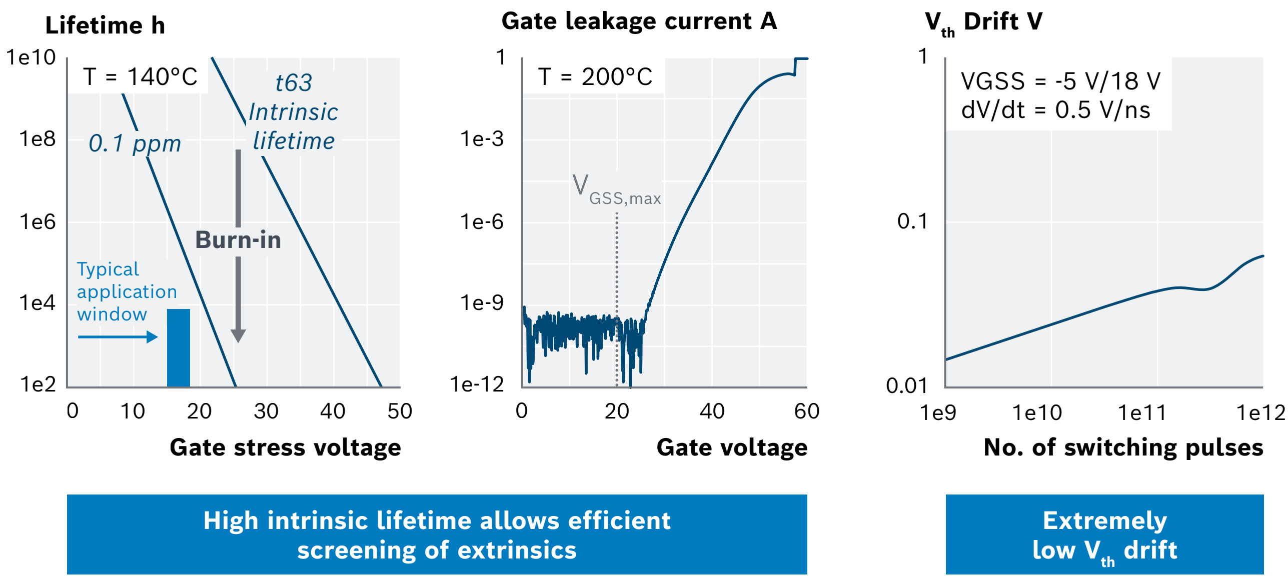


Figure 5: Exemplary lifetime, leakage current and V_{th} drift of gate oxide in Bosch's SiC MOSFETs.

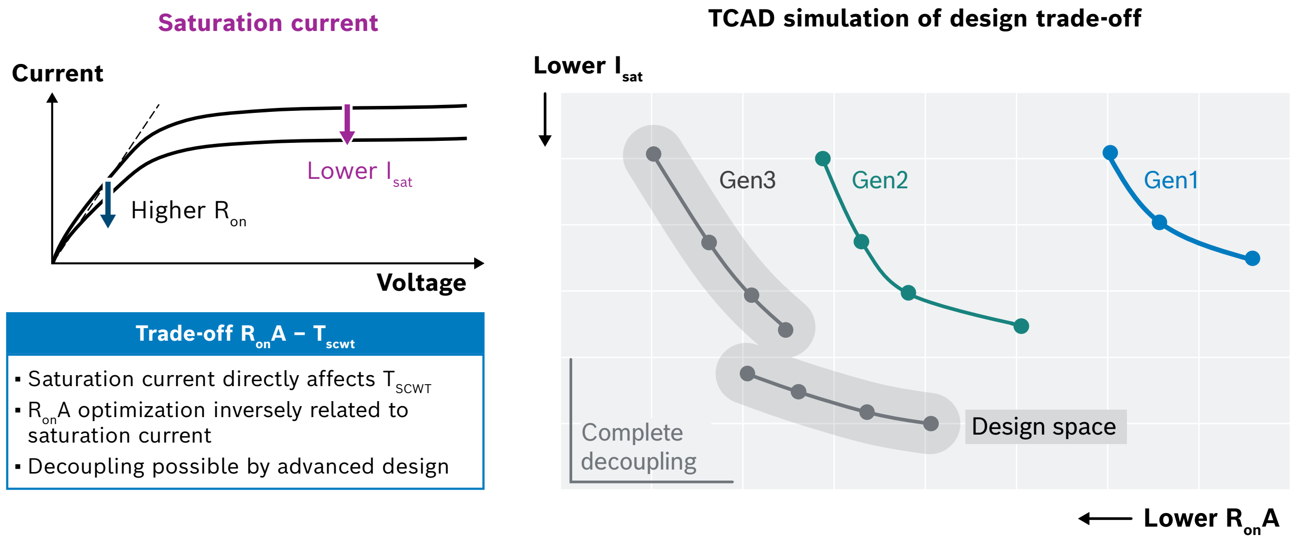
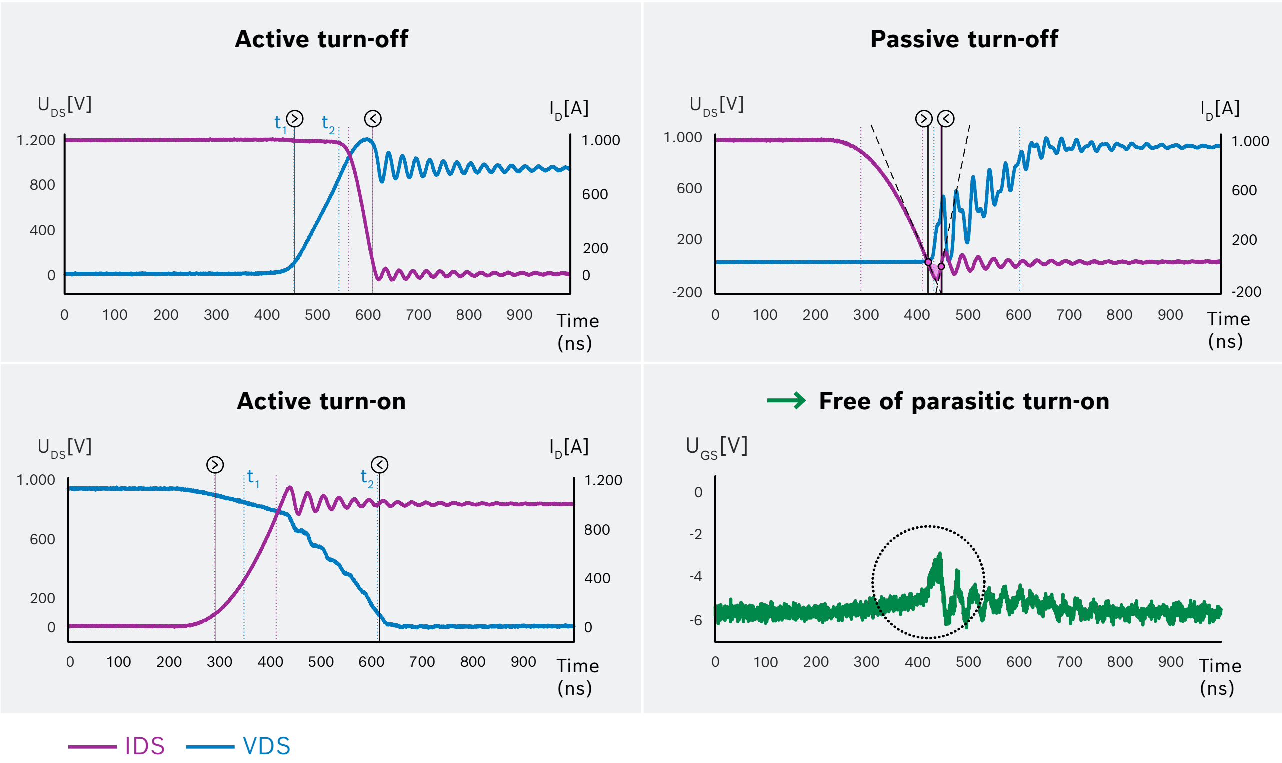


Figure 6: Graphical representation of trade-off between saturation current and specific on-resistance for SiC MOSFET generations from Bosch.

Optimized balance of performance and short-circuit robustness

There is always a trade-off between device performance and ruggedness. Bosch has significantly improved trade-offs such as between specific on-resistance (equivalent to die size at a given current) and saturation current (equivalent to improved short-circuit robustness) with each generation. A low specific on-resistance at a low saturation current is desirable for automotive traction inverter applications to deliver power transistors capable of handling high currents on low chip areas but also to ensure sufficient short-circuit ruggedness to meet the application requirements. In case of a short-circuit event, the SiC die needs to be able to handle very high current (the saturation current) for a certain amount of time. This time is known as short-circuit withstand capability. To have enough time to prevent the chip from being destroyed (i.e. shutting it off or lowering the current), the internal short-circuit withstand capability of the SiC chip needs to be longer than the time needed to detect the short-circuit event plus the reaction time of the gate driver plus the time needed for shutting off the chip. A good design of a SiC power MOSFET ensures the necessary level of short-circuit withstand capability while maintaining a low specific on-resistance. A low inductance module design and the use of advanced gate driving solutions (such as dedicated SiC gate drivers from Bosch) further lower the required intrinsic short-circuit withstand capability of the SiC MOSFET by reducing detection and reaction times. This makes it possible to push the trade-off towards even higher performance.

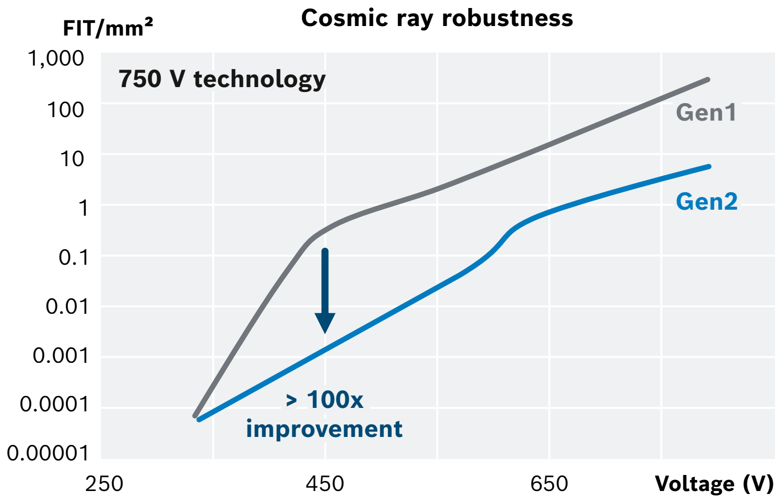
As a system supplier in the unique position of simultaneously developing, manufacturing, and using SiC MOSFETs, Bosch has tailored its technology to best match it to the respective application. For automotive traction inverters, an optimized behavior of the internal body diode ensures a favorable reverse recovery behavior over the full temperature range and a very good controllability of the maximum dV/dt. The latest generation of Bosch’s dual-channel trench technology eliminates the unwanted parasitic turn-on effect even at high dV/dt by surpressing capacitive coupling.



Optimized switching behavior	▪ Soft recovery over complete temperature range ▪ Very good controllability of maximum dV/dt ▪ No parasitic turn-on even at high dV/dt

Figure 7: Switching curves of Bosch‘s Gen3 SiC MOSFET engineering samples in module (1,000 A / 920 V).

Bosch understands automotive applications by heart and is feeding the extensive system knowledge back into the SiC MOSFET development. The definition of device parameters follows the application requirements. For example, the breakdown voltage of Bosch’s SiC MOSFETs is defined by the FIT rate, the origin of which is cosmic radiation in space. In contact with the earth’s atmosphere, this generates neutrons, which are unavoidable in standard automotive applications and can lead to total failure in high-voltage devices. Such particles can penetrate the components in the off-state and damage them. Hence, the device itself needs to be designed with a high level of resilience against such particles and a sufficiently high breakdown voltage. Since other failure modes are suppressed to such a large extent, the single event burn-out from the impact of cosmic radiation becomes decisive for the FIT rate. This approach ensures a low FIT rate in application-relevant mission profiles. Furthermore, transient overvoltage, which exceeds the voltage class rating, can be leveraged for improved switching behavior under fast switching conditions. This way, robust designs create additional benefits for the application without a significant loss of performance.



Breakdown voltage definition

- Mainly determined by
  - Cosmic ray robustness
  - Transient overvoltage capability
- SiC technology from Bosch with very low FIT since Gen2 (also in Gen3)
- Transient overvoltage above voltage class rating possible
  - → Benefit for fast switching

Figure 8: Exemplary FIT rate of Bosch's SiC MOSFETs in Gen1 and Gen2 architecture at varied drain voltages under cosmic ray exposure.

The device rating of SiC MOSFETs (750 V, 1,200 V) alone, however, is not enough to determine whether a device fits a specific application. A deep understanding of failure modes is essential to ensure robustness in both normal use and special operating conditions. This understanding makes it possible to push performance to the maximum without sacrificing robustness.

Substrates

The substrate is the foundation of any SiC semiconductor device. This raw material has a considerable influence on the chip yield and overall costs. Silicon carbide crystals contain a high number of defects which can be critical for the device yield, depending on their specific nature. Some of the defects can cause fatal failures during electrical testing or electrical stress. A deep understanding of defects in SiC raw material, their detection, and their impact on devices is crucial for a successful SiC device production and for securing a high level of reliability and robustness during application of field loads. Bosch is consistently investigating the entire supply chain of SiC substrates, from raw materials to the equipment and consumables for crystal growth and wafering.

Bosch's comprehensive substrate analysis

Bosch has deep insights into the quality and maturity of substrates from almost all suppliers. To analyze the parameters, Bosch has installed dedicated metrology tools in its facilities, such as the very powerful X-ray topography (XRT) with specific software to analyze the defect density of substrates. Figure 9 shows exemplary XRT analysis results of 200 mm material from a variety of suppliers. Two typical defect types, threading screw dislocation (TSD) and basal plane dislocation (BPD), are shown for material of more than 10 different 200 mm substrate suppliers, demonstrating significant variation. This deep knowledge of substrate quality and supplier maturity allows Bosch to strategically select the best suppliers from a huge number of potential vendors.

To ensure uninterrupted substrate supply, Bosch has established a diversified supplier portfolio following a multi-sourcing and multi-location strategy. Diversifying Bosch's supplier base across multiple regions significantly reduces its exposure to geopolitical tensions and possible trade barriers. Since 2024, the Bosch plant in Reutlingen has been using the innovative laser splitting process to produce some of the thin 200 mm substrates itself by wafering SiC crystals.

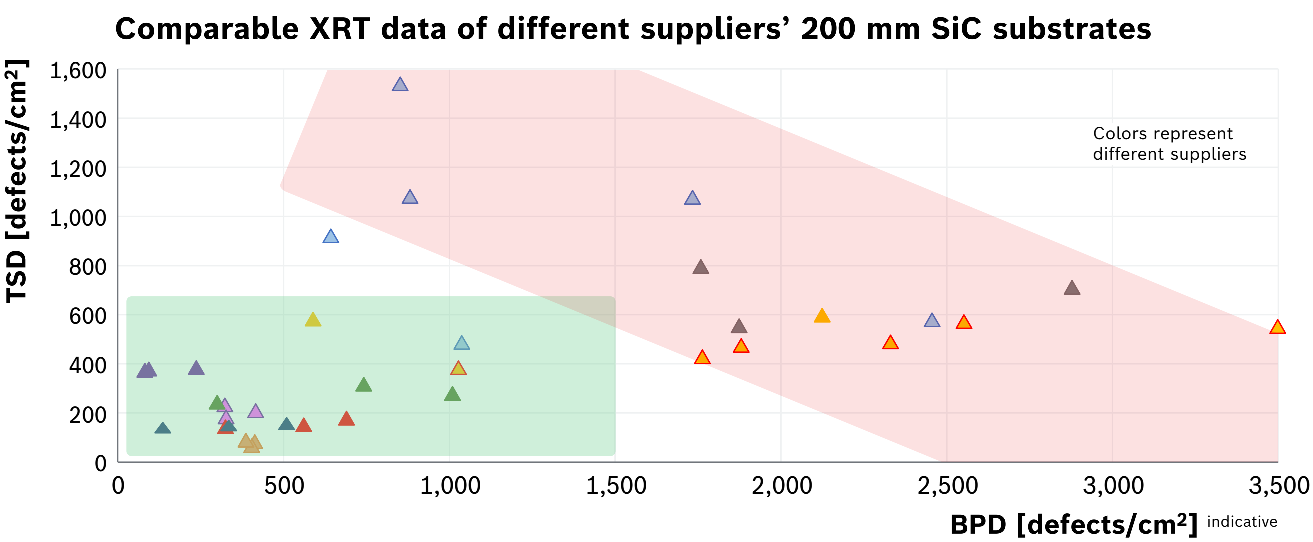


Figure 9: Defect analysis of more than 10 different 200 mm suppliers in 2022 and 2023.

Scaling SiC for the future: transitioning to 200 mm wafer sizes

The transition of SiC production technology from 150 mm to 200 mm wafer size is crucial to reduce the costs of SiC power chips and continuously improve device performance. Bosch's dual-channel SiC trench technology led to the first SiC trench MOSFET produced on 200 mm wafers, with initial samples used for customer qualification and evaluation in an electric vehicle in serial production. This underlines the strong position of Bosch as early adopter of 200 mm SiC technology and its high level of process control in SiC trench technology.

As mentioned before, material quality control is crucial for a successful transition to larger wafers. By using the wide portfolio of defect characterization tools on both substrate and epitaxy (epi), it enables a precise yield prediction. Killer defects, and therefore potentially defective chips, can be identified, allowing for the assessment and monitoring of substrate as well as epi quality at an early stage. These measures enabled Bosch to achieve 200 mm substrate quality that even exceeds 150 mm SiC substrate quality. Consequently, the transition to 200 mm makes it possible to exploit the full benefit of the larger number of SiC dies per wafer.

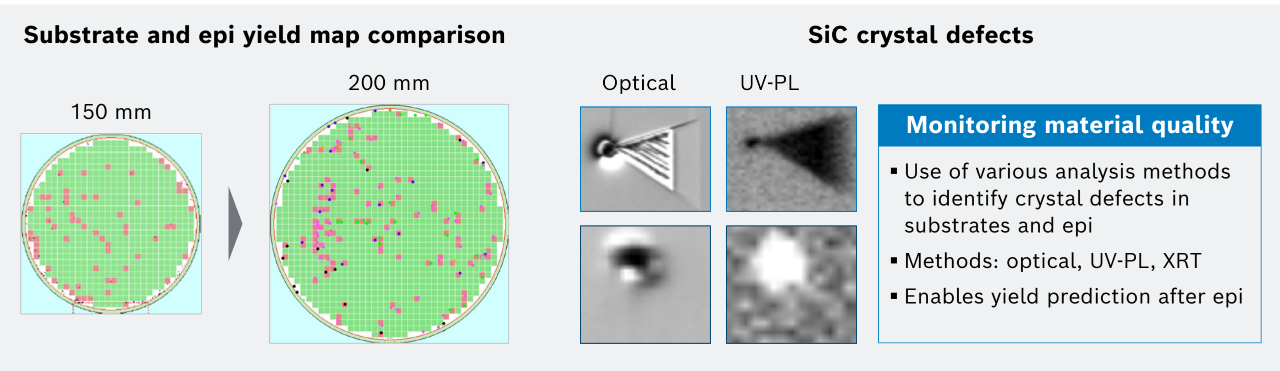
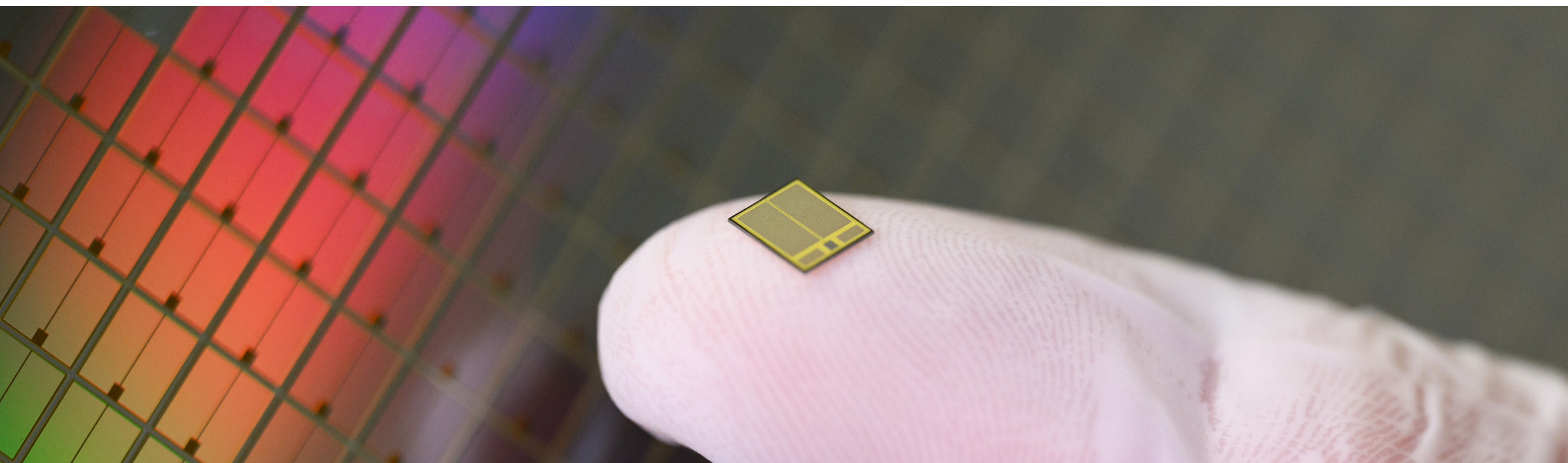


Figure 10: Exemplary epi yield prognosis after defect analysis of 150 mm and 200 mm SiC wafers.



Process enhancements and advanced chip designs

Apart from a larger number of good dies per wafer, the transition to 200 mm technology also offers benefits in process improvement and device design. The use of more sophisticated later generation 200 mm equipment can lead to a substantial improvement in process uniformity. As shown in figure 11 for the example of a thick hard mask etching process, the on-wafer homogeneity of this process is greatly improved on 200 mm. The same applies to other key processes such as lithography, which profits from better alignment as well as smaller critical dimensions on typical 200 mm equipment. The enhanced process capabilities enable more aggressive chip designs with narrower tolerances.

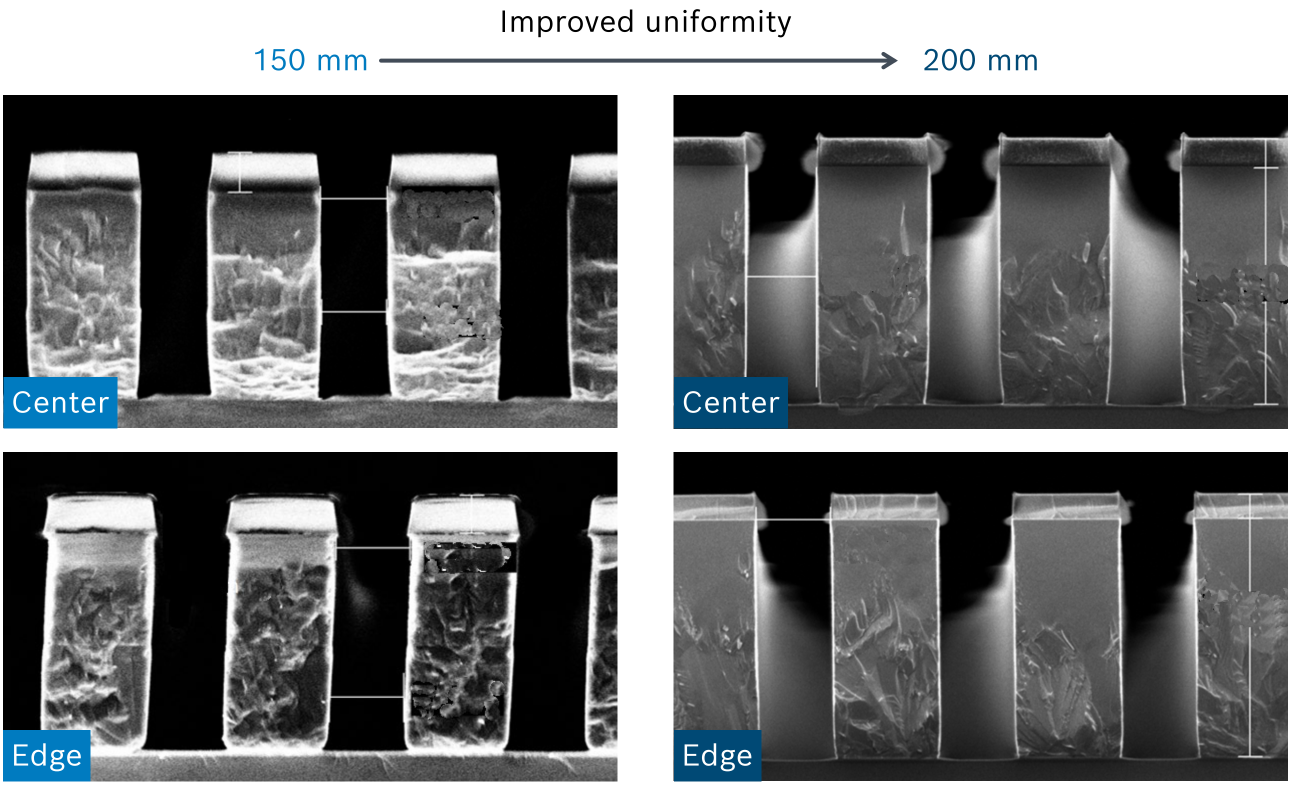
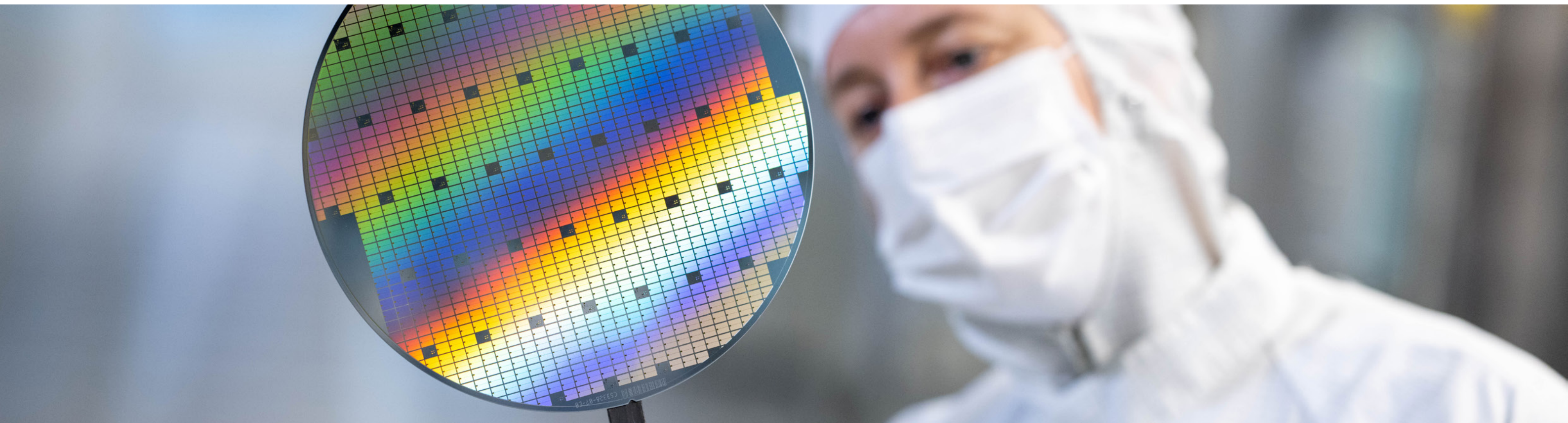


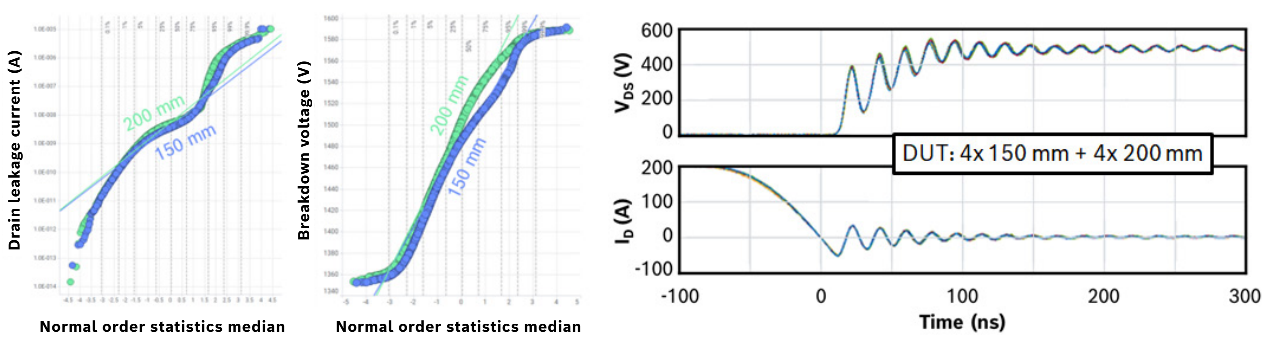
Figure 11: Example of hard mask uniformity used for ion implantation on 150 mm and 200 mm SiC wafers.



Successful technology transition

The key electric parameters are the final proof of a successful technology transition from one wafer size to a larger one. Figure 12 shows a comparison of the drain leakage current distribution for an identical SiC power transistor design manufactured on 150 mm and 200 mm wafers. The very good matching in the normal probability plots indicates a very similar defect density of the wafer and epi material. Bosch achieved this high degree of matching for all key device parameters, demonstrating a successful process transition from 150 mm to 200 mm SiC. The comparison of the switching curves (here of passive off-switching) of the same SiC MOSFET design manufactured on 150 mm and 200 mm respectively shows no visual difference between the 4 devices on 150 mm and the 4 devices on 200 mm. This underlines the successful process transition to the larger wafer size and proves that the baseline for leveraging the above-mentioned advantages from improved processes is given.

Matching of static performance | **Matching of dynamic performance**



Shown here: distribution of I_{DSS} and V_{BD}

Shown here: passive switching

Figure 12: Example of a comparison of the distribution of drain leakage current, breakdown voltage, and dynamic properties for an identical SiC power transistor design manufactured on 150 mm and 200 mm wafers.

05
Bosch’s SiC portfolio

Bosch offers customized SiC solutions for the mobility industry – power MOSFETs and power modules for various applications such as inverters, DC/DC converters, or onboard chargers. Bosch’s SiC MOSFETs are available as bare dies and discretes in various standard packages, or as power modules. All products are available in voltage classes 1,200 V and 750 V.

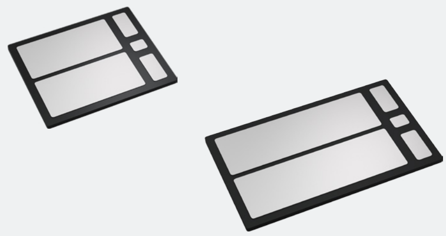
Bare dies

For customers who want to integrate their own designs into power modules, Bosch offers bare dies with different layouts and sizes to ensure maximum flexibility. Generation 2 bare dies with a voltage class of 1,200 V are available in the variants 8mOhm, 9mOhm, 11mOhm and 13mOhm. In addition, higher-ohmic bare dies in the range of 22-50mOhm are available in generations 1 and 2.

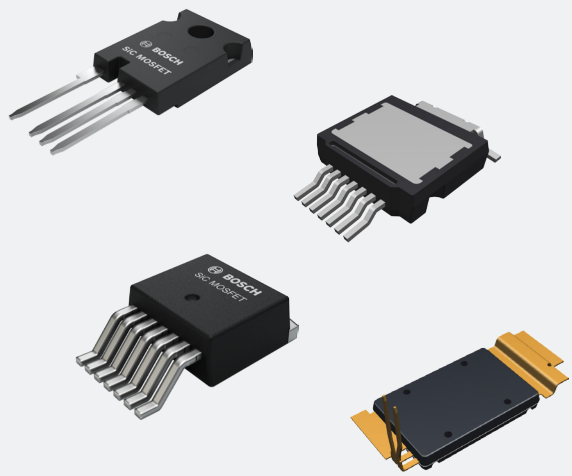
For the 750 V voltage class, generation 2 bare dies with 5mOhm and 6mOhm are available. In addition, there are higher-ohmic variants with 13mOhm and 28mOhm.

Customers can choose between different metallizations and additional design elements. Customized layouts are also available on request. All bare dies are designed for a maximum temperature of 175°C and 100 hours at 200°C and are based on the AEC-Q101 qualification.

SiC bare dies for inverters



SiC discretes for power conversion
(e. g. DC/DDC converter, on-board-charger)



SiC B6 modules on cooler

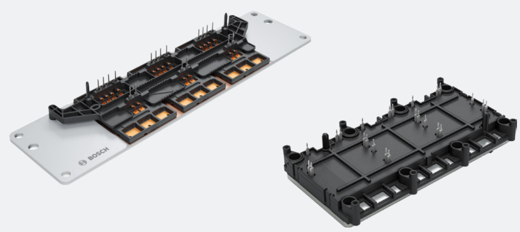


Figure 13: Bosch‘s customers can choose from a broad SiC MOSFET device portfolio.

Discretes

Discrete SiC MOSFETs are optimized for applications such as DC/DC converters, chargers (on-board chargers), or inverters for smaller motors. They are available in various standard packages that are market-compatible and take into account the requirements of the higher voltage class:

- TO-247-4L
- TO-263-7L
- HV-CPAK

All housings feature a Kelvin source connection for optimized switching performance and are designed for AEC-Q101 qualification. The portfolio includes

- 1,200 V: resistance ranges from 22 to 60mOhm
- 750 V: resistance ranges from 13mOhm and 28mOhm

Another discrete component is the Discrete SiC Line (DSL), which is designed for significantly higher currents and has weldable power connections. The footprint of the housing is market-compatible and optimized for inverter applications.

Power modules

Bosch's SiC MOSFETs are also available as B6 power modules on cooler. Various options are offered to flexibly cover a range of customer systems. All modules are designed for AQG 324.

Compact SiC Line (CSL) module
The CSL module is a frame module on PinFin cooler that is optimized for easy customer integration. It offers:

- 1,200 V: 275A and 355A
- 750 V: 420A and 515A
- Weldable power contacts for a low-inductance DC-link connection
- Compact dimensions of 158 x 84 mm^2
- Optional screw contacts
- Sintering technology on AMB & copper-bonded MOSFETs for increased robustness

PM6.1 module
The PM6.1 is a Bosch-proprietary, SiC-optimized design with the highest power density and a very compact layout. Features:

- Weld contacts for power connections
- Available with PinFin cooler or closed Al cooler
- Double-sided sintered SiC MOSFETs
- Sandwich construction with two ceramic substrates for a bond-free power path with high reliability
- 3D dimensional structure for high symmetry and low switching losses

In addition to these B6 power modules, the DSL is available as a single switch (see discrete) for inverter applications and offers maximum flexibility for system scaling.

The portfolio includes power classes for 750 V and 1,200 V.

EG120: isolated gate driver for SiC or IGBT power transistors
EG120 is a gate driver IC for SiC or IGBT power transistors up to 1,200 V. It is designed for automotive traction inverters, with optimized gate drive control to reduce load imbalance and switching losses. It features galvanic isolation, adjustable gate currents, intelligent profile selection, health monitoring, and AEC-Q104 qualifications.

Discover Bosch's SiC product portfolio:
https://www.bosch-semiconductors.com/products/sic-power-devices.

Publicly funded projects supporting SiC technology development

Collaborative projects – partnering for progress

Learn more

Important Projects of Common European Interest (IPCEI) – Semiconductors made in Europe

Learn more

The IPCEI ME/CT project is supported by the Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Parliament, by the Ministry for Economic Affairs, Labor and Tourism of Baden-Württemberg based on a decision of the State Parliament of Baden-Württemberg, the Free State of Saxony on the basis of the budget adopted by the Saxon State Parliament, the Bavarian State Ministry for Economic Affairs, Regional Development and Energy and financed by the European Union – NextGenerationEU.

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