Advances in SiC Technologies Address High-Voltage Electrification Design Challenges

By Ranbir Singh, PhD, EVP GeneSiC, Navitas Semiconductor

No-compromise device architecture addresses performance demands of next-generation power electronics applications

Abstract

The move to a more-electrified society that is critical for global environmental sustainability is a key driver behind the rapid growth in deployment of silicon carbide (SiC) semiconductors.

Capable of operating at higher voltages than their silicon counterparts, SiC devices in general offer superior efficiency, faster switching speeds and more robust operation – particularly at high temperatures. Now, devices at the 3.3 kV rating and above are becoming particularly important in higher-power applications.

In this article, Ranbir Singh, PhD, Navitas EVP, looks at the latest developments in GeneSiC technology, the benefits those bring to new and emerging high-voltage applications, and how such devices can be deployed.

Introduction

Driven by worldwide concerns over global warming and climate change, the world's economies are transitioning from fossil fuels to electrification, to deliver their energy requirements, from heating homes to powering transport. In moves towards decarbonization and meeting net-zero targets in many countries and enterprises, there is a pressing need to phase out the widespread use of fossil fuels. According to the United Nations, these account for 75% of global greenhouse gas emissions and nearly 90% of all carbon dioxide emissions[1], but still account for 80% of global energy production.

Supporting Electrification

Governments have put policies in place to encourage the move away from internal combustion engines and towards electric motors to power transport, including targets for ending the sale of new petrol-powered cars. Renewable energy has been contributing a growing share of the energy mix in many nations and in total at a global scale. Renewables now account for 29% of electricity generated in the world[3].

These alternatives to fossil fuels deliver power in electrical form, requiring investment in distribution networks, battery storage, and infrastructure to access the energy from the supply. As electrification grows, so must the infrastructure to support it.

Much of this market growth will come from EVs, some from the growth of solar power, energy storage and applications in industry. EVs still account for a minority of car sales in most countries but are growing fast. Sales in the US surpassed 5% of the passenger vehicle market in 2022, joining 18 other countries. Worldwide revenues from EVs are forecast to grow at 9.82% CAGR from $623.3B in 2024 to $906.7B in 2028[4].

Two factors still hold back many vehicle drivers from switching to electric models: range anxiety and charge times. For greater range, EVs need battery technology that is more efficient, smaller, and lighter. Cars powered by internal combustion engine can be filled up in five minutes; EVs take at least 25 minutes to reach 80% charge. Continued growth in EV adoption rests on investment in charging infrastructure, which is also growing, doubling from around $100B in 2023 to $200B in 2026[5].

Passenger EV manufacturers are aiming to cut charging times by as much as a half by migrating from 400 V batteries to 800 V batteries. The higher voltage (lower current) enables an increase in power by 50% to reach a peak of 350 kW. As well as increased power, the higher voltage reduces "I^2R" transmission losses, and increase rotational speed and torque in traction drives.

Furthermore, EV car batteries could have a role to play in the electricity infrastructure for the home. EV car batteries are on average four times the size of an average residential battery energy storage system (BESS), making their capacity more than enough to supply the energy needed by a typical household for a whole day. The parked car outside the home could be charged up in times of plentiful renewable energy, or when the cost is lower, and discharged back into the home at times of peak demand or when the cost is higher. Known as the 'vehicle-to-home' (V2H) approach, it could change the way households use energy in the future.

Using the car battery to store energy could also support grid stability by providing energy back to the grid (V2G). This capability could help to transform the grid, making it more intelligent and dynamic, able to store energy on a large scale to reduce demand on generators at peak times.

V2G and V2H charging requires bi-directional charging and discharging. EV manufacturers including Nissan and Ford have introduced on-board chargers (OBCs) with the technology ready for this capability.

Renewable energy is another highly-significant growth sector that requires high-voltage power conversion from solar panels, wind turbines, heat pumps and associated storage and where a number of synergies exist (Figure 1).

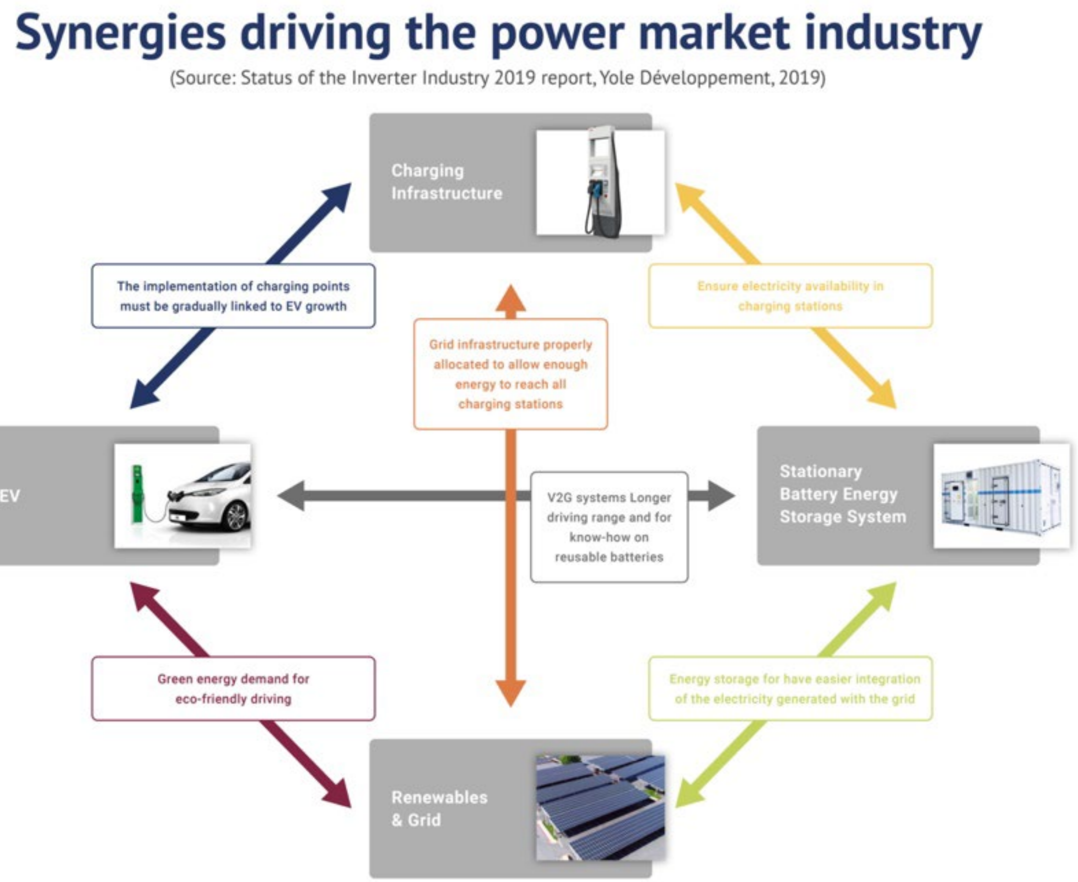


Figure 1: Synergies in the growing sector of renewables-generated electricity

Households and businesses are installing their own solar panels and BESS storage. The average US home needs 20-25 panels to provide 29 kWhr per day. However midday has the most daylight and generates the most power, but this is when the occupants tend to be out and using the least energy. Storing this energy means they can use it when they return, when the cost of electricity from the grid is at its highest. This energy can be saved to a home or business BESS, which includes a high-power conversion system (PCS).

In transport, manufacturers are also looking for more efficient and quieter power traction and other on-board power systems in trains, buses, lorries and vans. Power conversion systems are also used in wind turbine energy systems, grid distribution and motor drives that move everything from washing machines to robotics. Recent data is hard to come by, but a 2011 IEA report calculated they use 40% of the world's electricity[6], making them the world's single largest end-use of electrical power. Most AC motors are only 60% efficient. Variable speed designs could make motor drives significantly more efficient while reducing the energy and size of the drive required for a given task.

The Need for Silicon Carbide

SiC is inherently better suited to these growing applications in high-speed, high-power applications which are testing the limits of conventional silicon. SiC's stronger covalent bonds are comparable to those of diamond and give SiC a band-gap (the energy required to free an electron from its nuclear orbit) of 3.26 eV, which is nearly three times that of conventional silicon. This higher band-gap allows SiC to provide a dielectric breakdown strength ten times that of conventional silicon, and enables it to support higher speed operation, higher frequencies and higher voltages. SiC's superior thermal conductivity and stability also make it more reliable in high-voltage, high-temperature applications.

GaN is another wide band-gap material suitable for such applications but differences in thermal properties and electron mobility make it more suitable for some of these applications than others. SiC is particularly well-suited to applications where the key consideration is the ability to operate at higher voltages with strong power cycling capabilities.

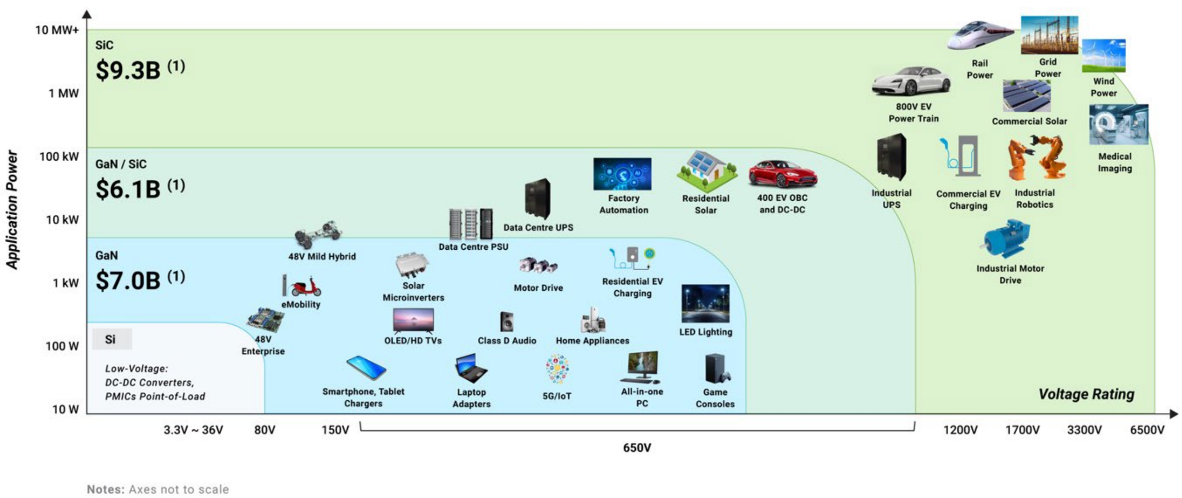


Figure 2: Application voltage ratings and power determine optimal semiconductor substrate types

Figure 2 plots some important and growing high power applications and groups them according to the most suitable power semiconductor architecture to meet their requirements. It is at the extreme voltage and power requirements that SiC performs best. Higher thermal conductivity and lower frequency operation make them a good fit for the higher power applications in the 1 kV to 20 MW region, such as those discussed above.

In renewable energy generation and grid distribution, the higher efficiency of all-SiC inverters will revolutionize the integration of renewable energy supply, storage, and delivery. SiC is used for example in inverters that aggregate the power from strings of panels and convert the generated DC into AC. SiC MOSFETs and diodes in the inverter and boost stages are more efficient than silicon and again contribute to reducing overall system size, weight, and cost.

In transport, SiC is also improving the fuel efficiency, weight and size of traction and other onboard power systems in trains, buses, planes and other vehicles. And in motor control, replacing the anti-parallel silicon diodes in motor current commutation with SiC is reducing switching and conduction losses; replacing all the power silicon IGBTs and diodes with SiC is even more efficient.

Market forecasters predict large dramatic growth for SiC as a result of growth in the markets for EVs, renewable energy and other end-use applications. The market will grow at 34% from $1.794 bn in 2022 to over $8.906 bn by 2028, according to Yole Développement (Figure 3). Mordor Intelligence forecasts over 25% compound annual growth in SiC power semiconductors from £2.18 bn in 2024 to $6.73 bn in 2029[8].

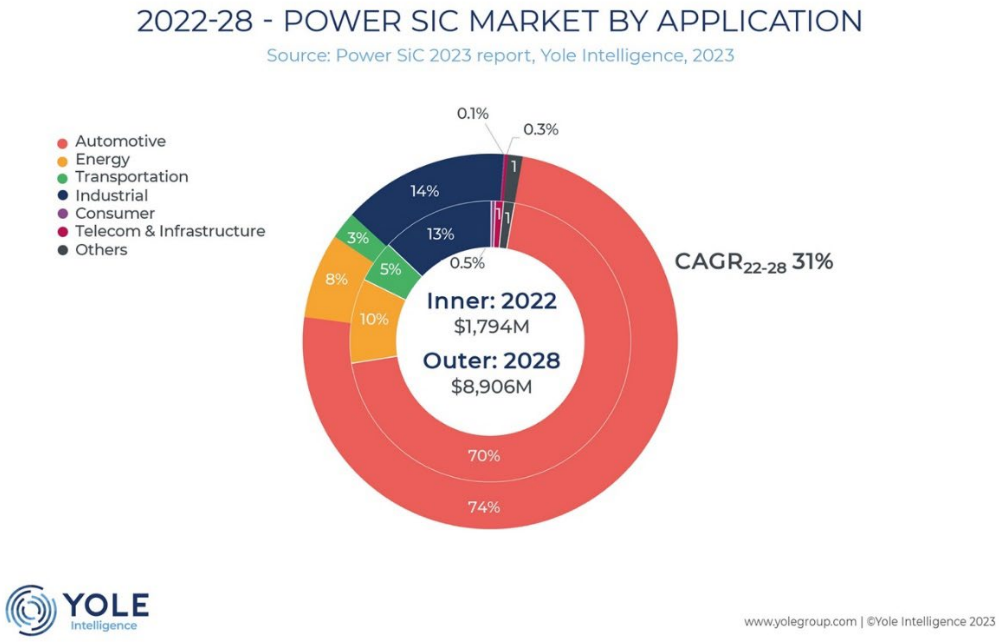


Figure 3: Projected SiC market by application[7]

The United States CHIPS act will boost manufacturing as 150 mm and 200 mm silicon wafer fabs, which are being superseded by 300 mm fabs for silicon production, are retrofitted for SiC production. The United States Department of Energy's (DOE) Advanced Research Projects Agency-Energy (ARPA-E) will invest $30M in 21 projects under the Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors (CIRCUITS) program. The US Department of Energy is also investing in research led by the National Renewable Energy Laboratory to further reduce the costs of manufacturing SiC power electronics.

Fabricating SiC Semiconductors

Planar or trench techniques have traditionally been used to fabricate SiC devices. Planar fabrication, depositing active device regions on the flat substrate surface, is relatively straightforward and familiar in the semiconductor industry through established use. For SiC it is high yield and low cost, and produces reliable devices but with slower switching and high drain-source on-resistance than devices made with trench techniques, which involve etching active device regions into the SiC substrate. However, traditional trench process tends to produce lower yields, and lower reliability at a higher cost.

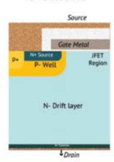
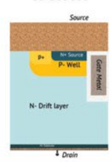
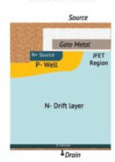
	Planar	Trench	GeneSiC
			
Manufacturability	» *Repeatable* » *High yield* » *Low cost*	» *Inconsistent trench etch* » *Lower yields* » *High cost*	» *Repeatable* » *High yield* » *Low cost*
Performance	» *High $R_{DS(ON)}$ / area* » *Slow switching* » *High $R_{DS(ON)}$ / Δ temp*	» *Lower $R_{DS(ON)}$ / area* » *Faster switching* » *High $R_{DS(ON)}$ / Δ temp*	» *Lower $R_{DS(ON)}$ / area* » *Fastest switching* » *Lowest $R_{DS(ON)}$ / Δ temp*
Reliability	» *Rugged gate oxide (stable V_{TH})*	» *Failures due to non-uniform gate oxide* » *Lower short-circuit capability*	» *Highest 100% tested avalanche* » *Long short-circuit withstand time* » *Rugged gate oxide (stable V_{TH})*

Figure 4: GeneSiC trench-assisted planar-gate fabrication compared to traditional trench or planar processes

By Ranbir Singh, PhD, EVP GeneSiC, Navitas Semiconductor,
Featured in IEEE, Volume: 11 Issue: 2

Navitas' patented, next-generation GeneSiC trench-assisted, planar-gate design combines the two approaches into a process that eliminates the compromises inherent in each (Figure 4). The process offers repeatable, high-yield manufacturing at a low cost. The design minimizes energy losses at high speeds, raising efficiency and performance levels. It produces reliable SiC MOSFETS with fast switching and enables the lowest on-state resistance, even at high temperatures.

This is important for applications where the devices are required to operate in challenging thermal conditions, as outlined above. In such applications, ambient system temperatures can rise to 80 °C, with even higher junction temperatures due to power cycling. GeneSiC technology enables the lowest commercially-available drain-source on-resistance temperature co-efficient (rated at 25 °C in the datasheet but it can also be much higher at higher temperatures) – Figure 5.

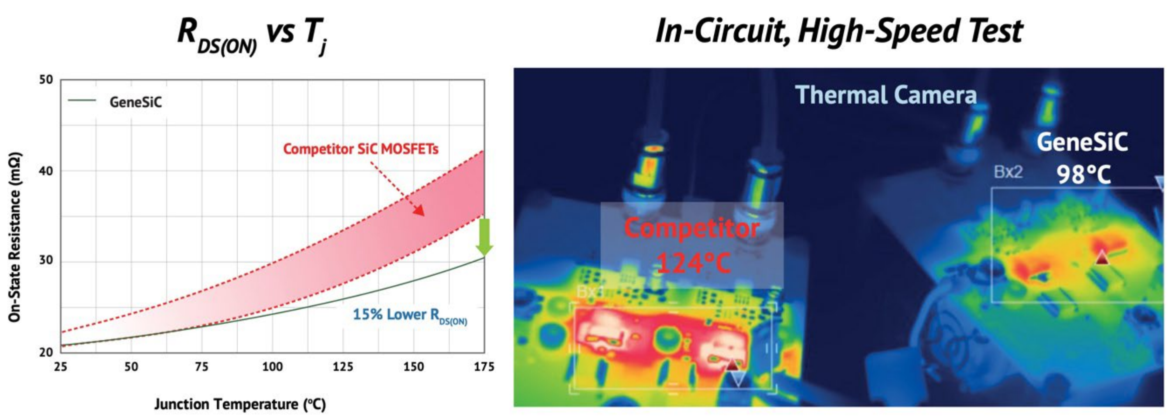


Figure 5: On-state resistance change with temperature

The trench-assisted, planar-gate approach produces diodes with improved efficiency (Figure 5) and lower forward voltage drops and produces MOSFETs with better switching speeds and lower conduction losses. Examples of these are the GeneSiC merged-PIN Schottky (MPS) diodes and the GeneSiC MOSFETs respectively. However, the integration of diodes within MOSFETs produces devices with all these improvements.

Navitas unveiled 5th-generation merged-PIN Schottky diodes at PCIM 2023, with low-built-in voltage biasing for superior FOM and robustness. Ideal for SMPS PFC applications, these diodes offer industry-leading efficiencies across loads. The innovative MPS diode design combines PiN and Schottky structures (Figure 6), resulting in the lowest V_F of 1.3 V, high I_{FSM}, and minimized switching losses.

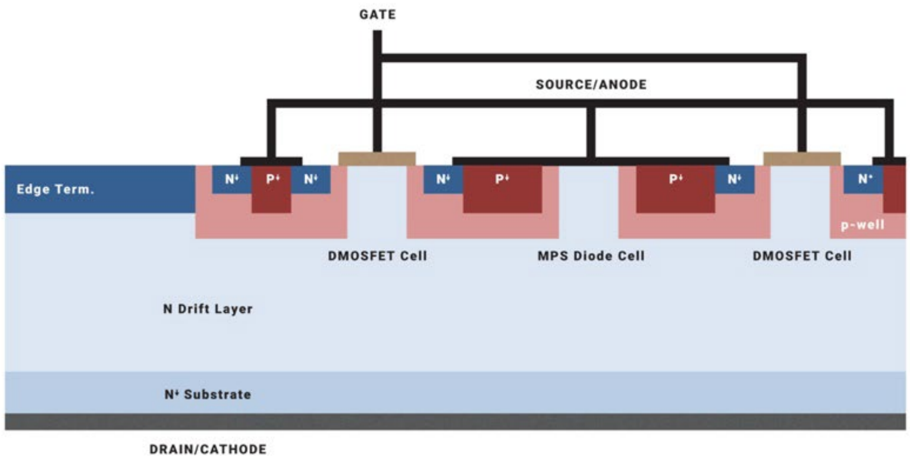


Figure 6: Structure of the GeneSiC MOSFET with monolithically-integrated MPS diode

Resistance parameters are also important for SiC MOSFETs. The Yole SystemPlus SiC Transistor 2022 Report compared the $R_{DS(ON)}$ characteristics of twelve SiC MOSFET technologies. GeneSiC's novel MOSFET technology outperformed all the others, including the trench-gate structures, while maintaining the ruggedness, short circuit capability and simpler manufacturing process of planar gate devices[10].

In tests, the GeneSiC 1200 V, 40 mΩ SiC MOSFET in a D2PAK outperformed the comparable leading competition, included in figure 5. Under equivalent conditions, GeneSiC MOSFETs exhibited a 25 °C cooler case temperature, reducing losses, higher system efficiency, and enhanced reliability, likely multiplying device lifetime threefold[10].

In 2019, GeneSiC worked with the Sandia National Laboratories and DoE on a monolithically-integrated SiC DMOSFET device structure with an integrated MPS diode. The product later won the Green Tech special recognition award at the 100 R&D Awards. Integrating such a diode provides improves bi-directional performance, temperature-independent switching, switching and conduction losses, reliability and the need for cooling.

A major technical problem with SiC MOSFETs up to 3.3 kV is basal plane dislocations (BPDs) faulting into Shockley-type stacking faults during 3rd quarter operation. In the integrated device, the built-in P-Well/N- Drift body diode of the MOSFET structure is bypassed, avoiding this BPD faulting within the N-drift layer of the MOSFET. The benefit in forward-voltage drop is shown in figure 7.

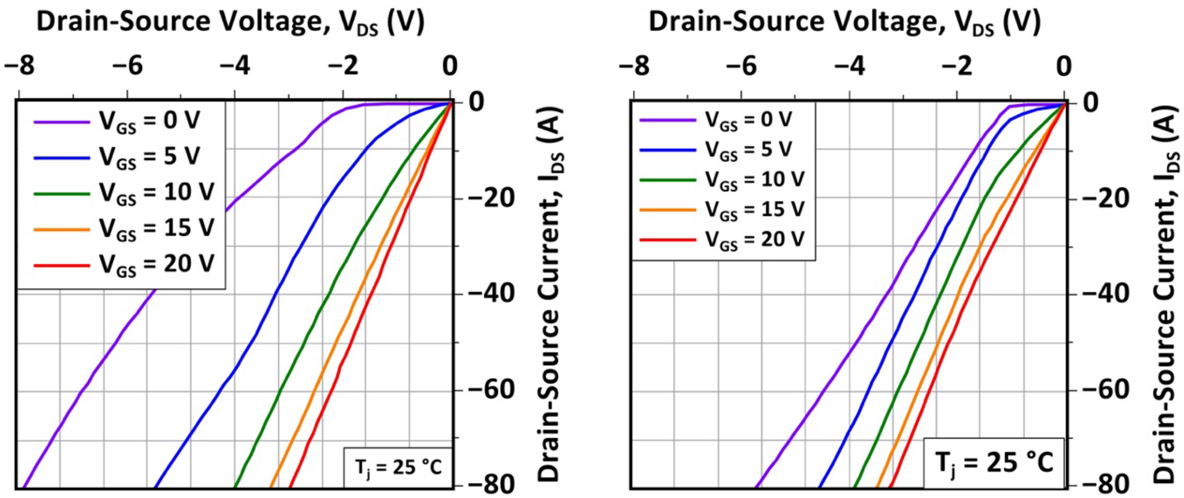


Figure 7: 3.3 kV Monolithic MOSFET with MPS diode (on right) has significantly lower voltage drop in third quadrant operation compared to a discrete SiC MOSFET (on left)

Deploying SiC

Deploying SiC devices has important consequences at system design level.

EVs moving from 400 V to 800 V batteries increases cuts transmission losses, heat dissipation, weight and cost in the power cables. However, the cables and motor windings require more insulation. The inverter system needs to be designed for the higher voltage. 1200 V SiC MOSFETs, with their efficiency and performance at higher voltages, are suited to such designs.

Replacing silicon with SiC in onboard chargers (OBC), DC-DC conversion, traction control and HVAC systems, leads to smaller batteries, motors, passive components, and EV as a whole, which lead to greater range, fuel efficiency and lower cost. The Genesis GV70 SUV, for example, can power from 10–80% in only 18 minutes using a Level 3, 800 V 350 kW DC charger[10].

An example of SiC implemented in an EV charger is the 350 kW-rated HDP350K fast charger. This converts 277 V_{AC} mains electricity to a controlled 200-950 VDC for both 400 and 800 V-rated battery-powered electric vehicles. Each charger utilizes 168 of the 1,700 V-rated GeneSiC GB10MPS17-247 components in the input power-factor correction (PFC) and output-rectifier stages for efficient and robust operation. GeneSiC parts operate up to 12°C cooler than competitors, attributed to their extremely-low threshold voltage (V_{TH}) characteristics, maximizing energy savings and promoting extended lifetime.

In the area of grid-connected energy storage (Figure 8), GeneSiC has collaborated with NC State University to develop a 3.3 kV SiC power module for grid-tied energy conversion systems. This innovation employs SiC MOSFET-Schottky-Diodes-Gate driver-based power modules and High-Frequency Magnetics-based Dual Active Bridge Circuits. The resulting bi-directional inverters, aimed at Lockheed Martin, boast conversion efficiencies exceeding 97.8%, offering reduced size, weight, and volume[11].

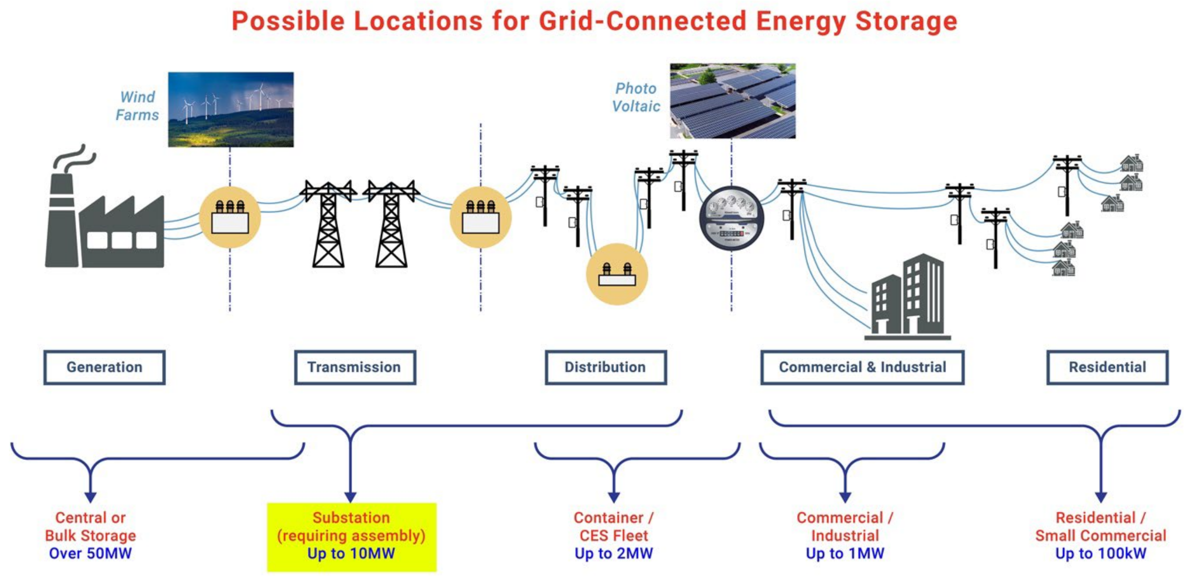


Figure 8: Power conversion electronics in energy storage devices will be important for the smart grid.

In the solar market, KATEK's Steca Coolcept FleX Series VII converts DC power from a string of solar panels into 4.6 kW AC power for use in the home, sending to the grid, or local storage. It uses sixteen GeneSiC 1200 V, 75 mΩ-rated SiC MOSFETs to provide a two-level converter, with bi-directional boost converters and an H4-topology for AC voltage output. The SiC technology's higher switching frequency reduces the size and weight of passive components.

The GeneSiC MOSFETs and Schottky MPS diodes already cover the industry's broadest voltage range, from 650 V to 6.5 kV.

GeneSiC technology has enabled many government agency projects to push SiC technology further: 6.5 kV SiC thyristors for energy-storage, grid-tied inverters for the Department of Energy; 15 kV MOSFET and PiN Diodes for defense applications; 500°C monolithically-integrated SiC super-junction transistor-JBS diode for NASA's Venus exploration missions; and monolithically-integrated, radiation-hardened SiC gate drivers for 1200 V SiC DMOSFETs and 6.5 kV SiC thyristors, for the US Navy.

Navitas continues to develop GeneSiC 6.5 kV SiC MOSFETs with the integrated Schottky diode, improving short-circuit robustness to be close to that of the discrete MOSFET devices. In recent research, the diode-integrated MOSFET failed during a 3,600 V, 5 µs long pulse of 2.9 J, compared to the discrete MOSFET that failed after turning off a 3600 V, 6 µs short-circuit pulse of 4.6 J.

Electrifying Our World: SiC the Accelerator

As we transition from fossil fuels to renewable energy, SiC is an accelerator in the reduction of CO_2 emissions. While a SiC FET requires more energy to create than a Si IGBT – due to SiC boule growth – the system benefits in terms of dematerialization and efficiency upgrades for higher-power, longer-lifetime systems, far outweigh the initial footprint. In fact, each SiC FET shipped is estimated to save 25.2 kg of CO_2 vs. legacy silicon IGBTs. SiC offers the potential to address a further reduction of 3.4 Gtons CO_2 /year by 2050[12].

References

1. SEI, IISD, ODI, Climate Analytics, CICERO, and UNEP. (2019). The Production Gap: The discrepancy between countries' planned fossil fuel production and global production levels consistent with limiting warming to 1.5°C or 2°C. http://productiongap.org/
2. IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)
3. IEA (2021), Global Energy Review 2021, IEA, Paris https://www.iea.org/reports/global-energy-review-2021, License: CC BY 4.0
4. Statista Market Insights, Sep 2023. https://www.statista.com/outlook/mmo/electric-vehicles/worldwide#unit-sales
5. According to Bloomberg NEF estimates 2024-2026
6. IEA (2011), Walking the Torque, IEA, Paris https://www.iea.org/reports/walking-the-torque, License: CC BY 4.0
7. Power SiC 2023, Yole Intelligence, 2023
8. Mordor Intelligence, Silicon Carbide Power Semiconductor Market Size 2019-2029 Source: https://www.mordorintelligence.com/industry-reports/silicon-carbide-power-semiconductor-market
9. A. Marzoughi et al. IEEE Trans. Industrial Electronics, 64(10), pp.8247-8257 (2017)
10. The Genesis of GeneSiC and the Future of Silicon Carbide, EE Power, July 11, 2023 by Llewellyn Vaughan-Edmunds https://eepower.com/technical-articles/the-genesis-of-genesic-and-the-future-of-silicon-carbide/
11. Advanced Power Conversion Systems featuring SiC MOSFETs with in-situ restoration capabilities, GeneSiC/NC State Univ.
12. Sustainability Report 2022, Navitas, https://navitassemi.com/sustainability-report-2022/

About Author

Ranbir Singh joined Navitas with the acquisition on GeneSiC Semiconductor, which he founded in 2004. Ranbir has dedicated his life to the mission of high-performance, high-reliability semiconductors, and is highly respected in the power electronics community, with several awards, over 200 journal and conference papers, plus over 30 US patents. Ranbir holds a Bachelor of Technology, Electrical Engineering from the Indian Institute of Technology, Delhi, and both Master's and PhD in Electrical Engineering – Power Semiconductors, from North Carolina State University, Raleigh.