How the unique properties of wide bandgap materials improve application performance

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THE ADVENT OF SILICON CARBIDE PAVES THE WAY FOR LARGE-SCALE ADOPTION OF WIDE BANDGAP SEMICONDUCTORS

In power electronics, Silicon (Si) has been adopted as the mainstream technology over the last four decades; today, silicon power transistors and diodes are so widespread and pervasive that equipment based on this material is closely intertwined with our everyday lives. This adoption has allowed silicon to enjoy continuous technology and process improvements, supported by innovative packaging and interconnect technologies, that have enhanced thermal management and reduced parasitic effects for higher frequency operation. By virtue of this unrelenting quest for improvement, silicon technology is about to reach a plateau where further iterations can be only incremental. Recently, wide band gap semiconductors have taken over silicon thanks to their unique properties.

The use of Silicon Carbide (SiC) devices in power electronics has been proposed since the 60s, its wide band-gap and other features offering the prospect of high efficiency operation. However, some difficulties in manufacturing substrates for SiC wafers have delayed the development of SiC power devices. The main challenge stymying their adoption has been their cost, associated with the limited availability of high-quality SiC material, the cost of SiC wafers, and SiC manufacturing problems of larger wafer diameter, defect densities, and yield. The recent supply of good-quality SiC wafer substrates offered by different suppliers has helped to circumvent these issues; finally, the increased competition has pushed down wafer prices.

- WBG products allow for higher energy conversion efficiency
- SiC has already made inroads into Automotive
- GaN comes next as silicon contender in high-volume applications

In contrast to SiC power devices that have been around for quite a while, Gallium Nitride (GaN) power devices have just started to appear in the market. GaN offers many of the performance benefits of SiC with the prospect of accrued competitiveness because it is grown on a larger, lower-cost Si substrate and can be produced in renovated CMOS fabs. However, the technologies used in SiC and GaN power switches are quite dissimilar. The SiC for instance is a harder material and requires more sophisticated manufacturing techniques at far higher temperatures with respect to silicon; annealing is done at 1700 °C and ion implantation at 500 °C vs. 800 °C and 25 °C, respectively.

GaN switches, on the other hand, are derived from RF HEMT (high electron-mobility transistors) technology, which differs from that of the silicon power FET.

As a key supplier of power solutions, STMicroelectronics has heightened efforts to complement its offer with wide bandgap materials (WBG) such as Silicon Carbide (SiC) and Gallium Nitride (GaN). The two technologies owe their appeal essentially to their capability to operate at higher voltages without compromising on-state performance; they can handle far higher temperatures more safely and can work at higher frequencies. Their physical and electrical characteristics make it possible to reach unrivalled levels of miniaturization, reliability and power density, all necessary features in demanding applications such as electrical-vehicles (EV) inverters and chargers, datacenter converters and industrial drives, to name just a few. Environmental concerns so widely debated in the media and under the spotlight to drive governments' policies over our energy future, can therefore be addressed by a large-scale rollout of the new compound semiconductors. To help you better understand the potential performance benefits, the following table summarizes the main properties of silicon vs. SiC (4H polytype) and GaN.

	Si	SiC-4H	GaN
Bandgap (eV)	1.1	3.2	3.4
Electron mobility μ_n (cm^2/V s)	1450	900	2000
Breakdown Electric Field E_{br} (MV/cm)	0.3	3	3.5
Saturation electron drift velocity V_s (10^7 cm/sec)	1	2.2	2.5
Thermal conductivity Θ (W/cm K)	1.5	3.8	1.3

Table 1: Physical properties of wide bandgap semiconductors compared to Silicon

BENEFITS OF SiC MOSFETS AND GaN HEMTs IN VARIOUS APPLICATIONS

Early efforts to fit SiC technology into stringent automotive requirements by conducting extensive tests have proved successful for ST, allowing the company to deliver planar SiC MOSFETs in volume to the electric car industry for the main inverter, DC-DC converter and OBC. Moreover, STPOWER SiC MOSFETs lend themselves to power charging stations, the backbone of a global infrastructure. Also, the deployment of silicon carbide in Automotive not only is helping to address other application areas in the industrial domain but is also directing designers to conceive future generations for space and avionic applications.

SiC MOSFETs and GaN HEMTs are largely complementary as each one of them addresses different applications. EVs are benefiting from large-scale adoption of both, with SiC MOSFETs and their ability to operate at voltages between 650V and 1600V, being ideal for traction inverters, DC-DC converters and on-board chargers (OBC). Operating at voltages from 650V down to 100V, GaN may eventually also be a valuable technology for the latter two applications, due to its higher frequency capability, as it becomes more mature and cost effective.

ST'S LONG HISTORY WITH SILICON CARBIDE

The STPOWER SiC MOSFET lineup is the result of ST's prescient vision and focused investments in innovation and development dating back to the mid-90s and to the collaboration efforts with research institutes. The capabilities of silicon carbide have been properly assessed over the years resulting in ST having achieved an undisputable leadership position.

PLANAR VS. TRENCH TECHNOLOGIES: THE SiC MOSFET ROADMAP

The SiC MOSFET shares the same vertical structure as its silicon counterpart with a gate oxide as one of the main building blocks. In silicon, MOSFETs and IGBTs planar structures have long been replaced by more performing trench and super-junction variants even if it took years for designers to accommodate the new technologies. It would be almost straightforward to question why ST together with other main competitors is still opting for the planar structure and not incorporating all advancements and benefits that the trench process has allowed so far. It is worth saying that the 2nd generation planar is being produced in high volumes and has helped ST establish its leadership in the market. The next iteration of the SiC MOSFET (3rd generation) will deliver even more improved specific on-resistance figures-of-merit and also a possible further generation could be feasible which is still based on planar techniques. While trench technology is still in ST's roadmap as a long-term endeavor, nevertheless there are some hurdles and issues to be solved before the new technology is made rugged enough to be safely deployed. In any case the potential features of the planar technology have not been exploited to their full extent.

DESIGN ADVANTAGES OF USING SiC MOSFETs

In spite of its being a new material still subject to deep investigations, ST has successfully proposed the SiC technology for EV applications, therefore contributing to stepping up car electrification. We can thus quantify the benefits of a SiC MOSFET by considering a 210kW inverter and compare it against a silicon solution like an IGBT (plus freewheeling diodes) in terms of total chip area and losses. Realistically we are assuming 10kHz operation and 800V bus that is becoming the main choice for car makers. The following figure shows the main EV blocks; the OBC and the DC-DC converter can also benefit from using SiC MOSFETs whereas Table 2 summarizes total losses and chip area when using a silicon IGBT and a SiC MOSFET.

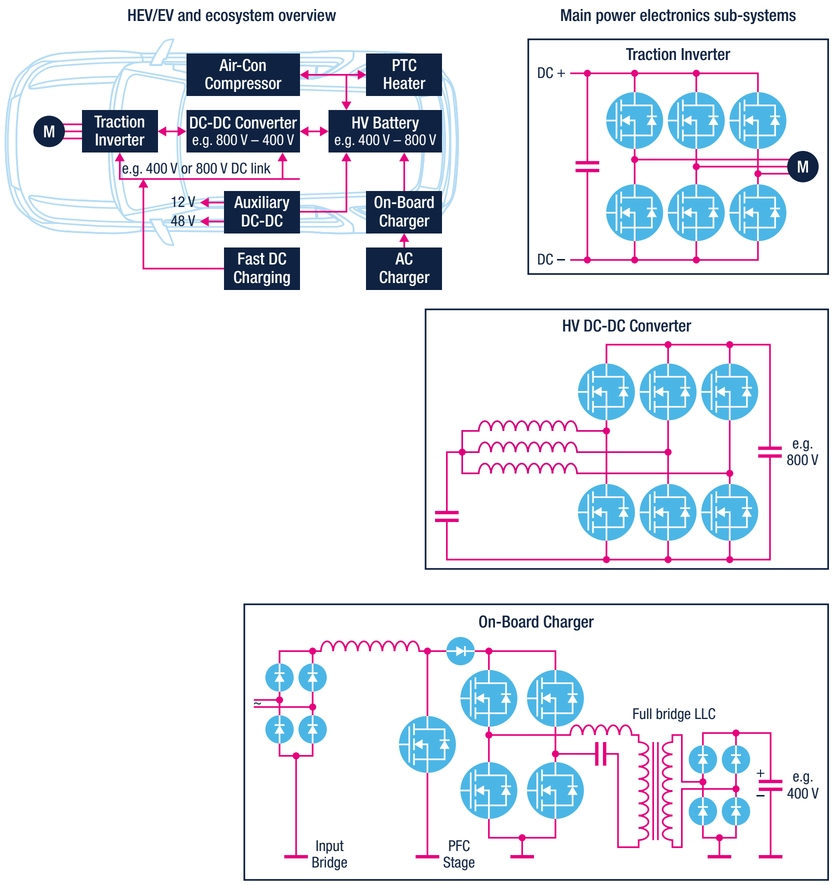
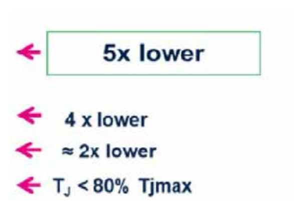


Figure 1: EV building blocks

Depending upon the load, the gain in efficiency varies from 3 to 8%. Even more impressive, it achieves this better efficiency in chips that are 5 times smaller!

10 kHz		
Losses*	**IGBT commercial product**	**Full-SiC 1200V**
Total chip-area	400 mm² (IGBT) + 200 mm² (diode)	120 mm²
Conduction losses* (W)	300	307
Switching losses* (W)	564	143
(S1+D1) Total losses* (W)	864	450
Junction Temperature (°C)	134.8	132.4



*: Typical power losses per switch at peak power: 350 A_{rms}

Table 2: Chip area and total losses: a comparison

Figure 2 depicts the losses split, between conduction and switching, as a function of load. Overall, by virtue of the drastic reduction in losses, the size of the PCU (power control unit) can be reduced by 50% which in turn enables a cost reduction of the cooling system.

Power loss comparison at nominal continuous phase current @ 10kHz

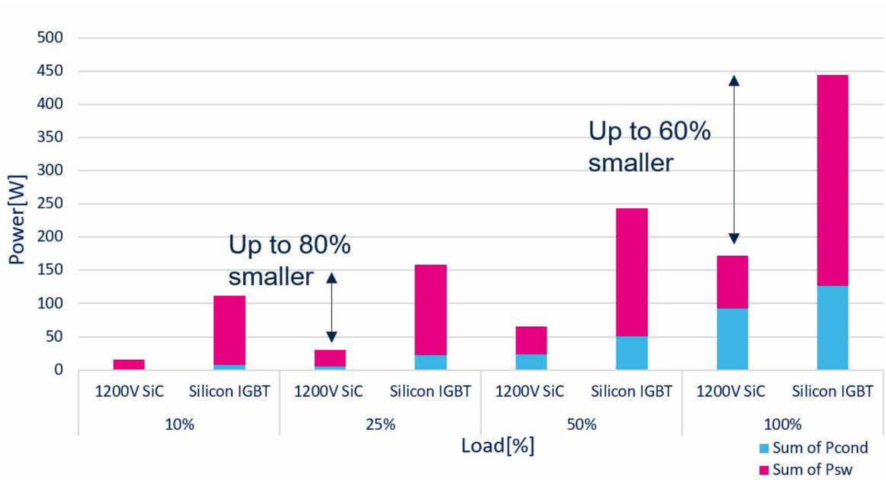
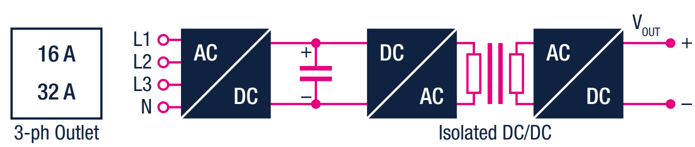


Figure 2: EV building blocks

Another interesting evaluation involves the use of SiC MOSFETs in a bi-directional OBC.



Parameter	Value
Input voltage	L_X-L_Y → 400 V_{AC} L_X-N → 230 V_{AC}
DC link voltage	400..1000 V
Normal power	11..22 kW
Output voltage	200..500 V_{DC} for 400 V_{DC} Batteries 500..900 V_{DC} for 800 V_{DC} Batteries

Table 3: General structure of an OBC

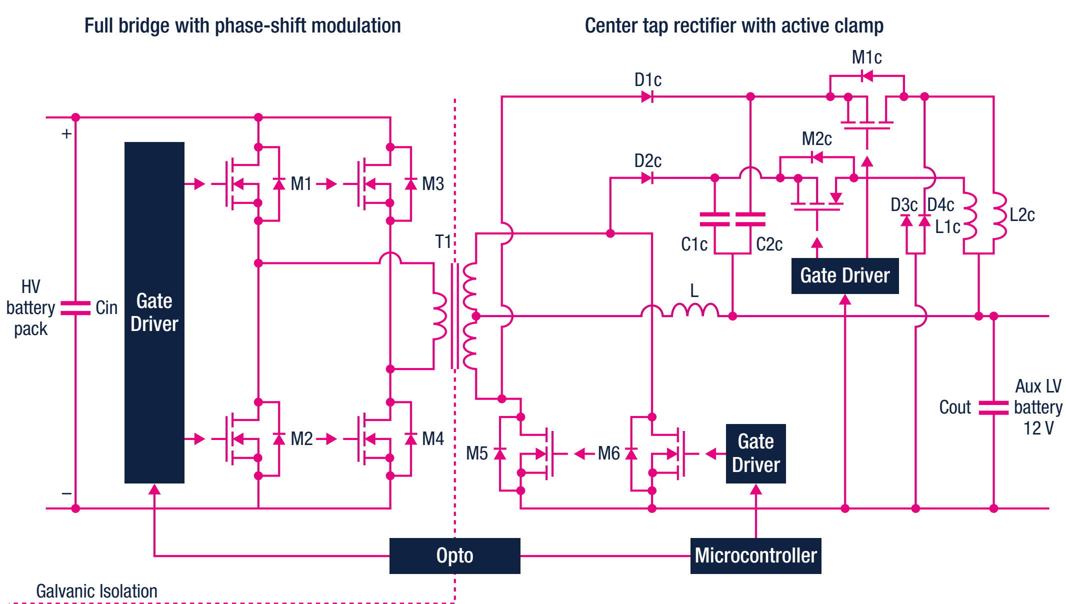


Figure 3: Circuit implementation of bi-directional OBC

A circuit implementation of a bi-directional OBC is indicated in Table 4 where the SiC MOSFET in this case is benchmarked to a silicon super-junction MOSFET. This topology has a very important feature in that high-voltage batteries can also be charged by the 12V battery thanks to the reverse flow of energy.

Load [W]	P_{TOT} [W]		Efficiency [%]	
	Si MOSFET	SiC MOSFET*	Si MOSFET	SiC MOSFET
150	2.86	0.63	87.63	91.01
230	3.09	0.71	88.58	91.53
400	3.714	0.89	88.79	91.73
600	4.49	1.19	88.63	90.40
1000	6	1.84	85.73	86.48

Table 4: Table summarizing comparison between SiC and Si MOSFETs

As can be seen at all load conditions, total losses are on average 3 times lower for the SiC MOSFET resulting in higher conversion efficiency. It is also worth noting that topologies for both the DC-DC converter and OBC are derived from industrial applications so the SiC technology addresses both sectors delivering the same benefits.

Let's look at another example, a central storage system with 1MW of installed power (Figure 4). Assuming an efficiency increase of 4%, which is within our reach when using SiC MOSFETs, we can save 40,000kWh of energy in one year. And let's just think of doing this on a regular basis!

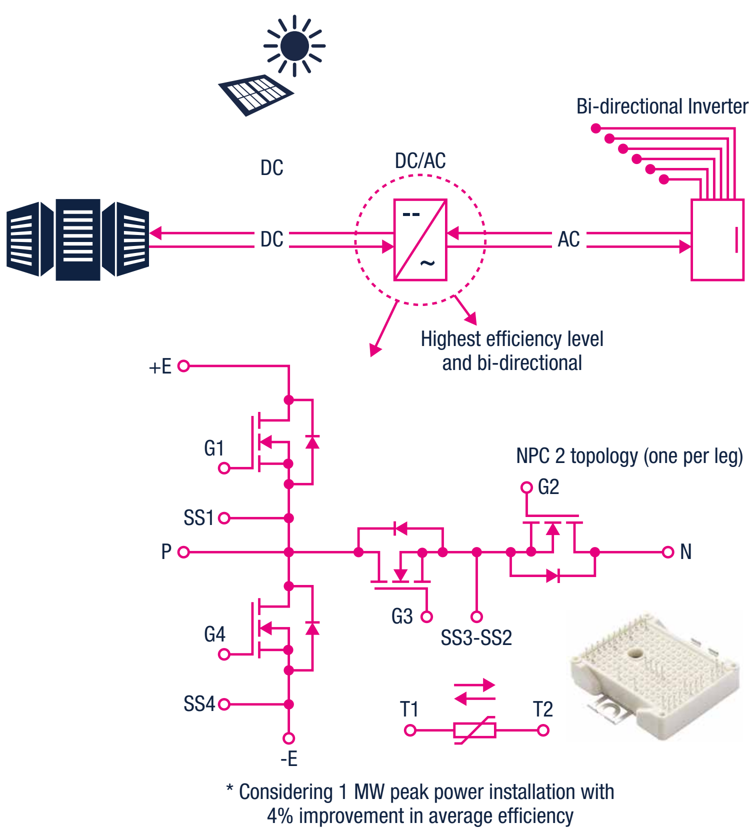


Figure 4: Bi-directional SiC-based storage system

BENEFITS OF USING GaN DEVICES AND THEIR FUTURE POTENTIAL

GaN HEMTs are starting to make inroads into a wide range of applications such as OBC, wireless charging, point-of-loads (POL), photovoltaic micro-inverters, switching power supplies and adaptors, etc., exploiting their superior performance in terms of low on-resistance, low capacitances and gate charge, therefore high operating frequencies. This is also possible considering the voltage range they can cover which extends from 100V to 650V/900V. In so doing they will help designers achieve higher conversion efficiencies, smaller form factors and therefore push power density up to reach new challenging and unrivalled targets.

Owing to such properties, not only traditional topologies deliver superior performance, but also new circuit concepts are being enabled by their use. For instance, an efficiency of 99% can be reached in totem-pole PFC circuits providing high efficiency and increased power density. Generally, bridgeless PFC has lower on-losses than traditional PFC by virtue of a reduced number of active semiconductor devices from three to two. A totem-pole bridgeless topology is also used because of its lower EMI noise with respect to other bridgeless topologies.

Another example of a high-volume application benefiting from GaN usage is the Active Clamp Flyback (ACF) converter employed in PC travel adaptors and USB wall chargers. In this topology (Figure 5), the standard diode of a conventional flyback circuit can be replaced by a secondary switch (S2). Thanks to low switching losses (zero voltage switching) and the transformer's leakage energy re-utilization, it can be used at high frequencies reducing adaptors' size and weight significantly.

Thanks to their superior performance, GaN HEMTs help designers achieve higher conversion efficiencies, smaller form factors and therefore push power density up to reach new challenging and unrivalled targets.

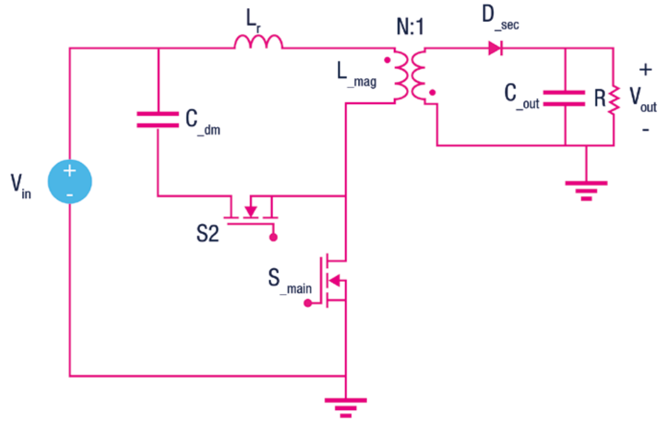


Figure 5: GaN in ACF topology for chargers

CONCLUSION

Power electronics designers have been waiting for breakthrough technologies in order to reshuffle circuit topologies and boost efficiency in energy conversion systems. The SiC technology perfectly matches these expectations. The time is over when people tinkered with silicon carbide as a naïve technology to be tested in labs. Today ST is producing SiC MOSFETs and diodes in very large volumes suiting a large spectrum of applications. We are currently helping many customers develop their future applications who appreciate the very significant potential of these innovations. A new era marked by the Nth revolution is ahead of us.

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