Wide-bandgap semiconductors: Performance and benefits of GaN versus SiC

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Introduction

Gallium nitride (GaN) and silicon carbide (SiC) FETs are enabling higher levels of power density and efficiency compared to traditional silicon metal-oxide semiconductor field-effect transistors (MOSFETs). Although both technologies are wide bandgap, there are fundamental differences between GaN and SiC that makes one a better fit than the other in certain topologies and applications. The purpose of this article is to compare the two; discuss the differences in switching performance, cost and applications; and explain the technology each provides.

High-voltage power devices

The world of power electronics witnessed a breakthrough in the 1950s when two engineers at Bell Labs invented the MOSFET. The first commercial MOSFET was released to production a few years later.

The introduction of insulated gate bipolar transistors (IGBTs) in the 1980s offered another alternative for higher-power and high-voltage applications compared to traditional silicon-controlled rectifier and gate-turnoff thyristor devices. IGBTs became the industry's workhorse for applications such as AC and DC drives, traction inverters, uninterruptible power supplies and induction heaters. The switching frequency in these applications is typically no higher than 20 kHz.

The commercialization of wide-bandgap devices such as GaN and SiC has changed the landscape of the power industry once again. These devices offer substantial improvements over both MOSFETs and IGBTs, including low gate capacitance to enable faster turnon and turnoff, while reducing gate drive losses. For instance, GaN offers a gate charge of less than 1 nC-Ω, versus 4 nC-Ω for silicon. These devices also offer significantly lower output capacitance, enabling designers to achieve higher switching frequencies without an increase in associated switching losses, and to shrink the size and weight of magnetics in the system. A typical GaN device has an output charge of 5 nC-Ω versus comparable silicon at 25 nC-Ω.

All of these high-voltage devices have distinct characteristics, and as shown in Figure 1, each has different power levels and switching frequencies.

Comparing GaN and SiC performance

GaN and SiC serve different power needs in the market. SiC devices offer voltage levels as high as 1,200 V with high current-carrying capabilities. This makes them a good fit for applications such as automotive and locomotive traction inverters, high-power solar farms and large three-phase grid converters.

GaN FETs, on the other hand, are typically 600-V devices and can enable high-density converters in the range of 10 kW and higher. GaN applications include consumer, server, telecom and industrial power supplies; servo drivers; grid converters; electric vehicle onboard chargers and DC/DC converters.

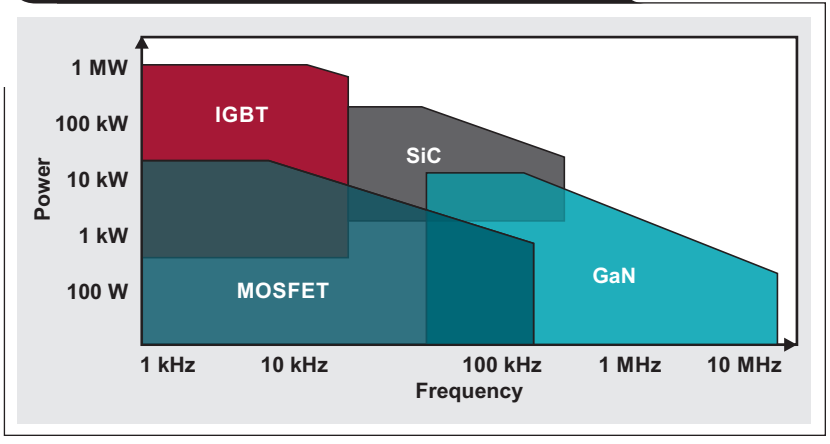
Despite these differences, the two technologies do overlap in some applications below 10 kW. The following are two specific examples.

Single-phase PFC

Every line-powered electrical product consuming more than 75 W requires power factor correction (PFC). PFC is the first power-conversion stage between the grid and the system and carries the entire load at any given operating point. Therefore, its efficiency and power density directly impact overall system size. In single-phase grid-connected applications, PFC stages are typically designed for a universal AC input (85 V_{AC} to 264 V_{AC}) and have output voltages as high as 400 V_{DC}.

Designers have used different topologies with the goal of reducing size while meeting industry efficiency standards. The efficiency levels defined in 80 PLUS® specifications, for instance, are 96% for titanium-grade power supplies.

Figure 1. High-voltage power device mapping



The dual boost topology shown in Figure 2a is a popular choice in high-power systems greater than 1 kW. The introduction of SiC diodes and the latest generation of superjunction (SJ) MOSFET transistors have facilitated some improvements in power density and efficiency. These improvements, however, have reached a plateau in the last decade.

The totem-pole topology shown in Figure 2b provides a cost-effective alternative to dual-boost PFC by reducing the number of power devices and inductors by half, while significantly increasing the density and efficiency. Totem-pole solutions with either SiC or GaN devices are available. GaN offers a number of advantages over SiC in this topology, however, including:

- **Zero reverse recovery.** Unlike MOSFETs, there is no P-channel N-channel junction within the lateral structure of a GaN FET; thus, there are no body-diode and associated reverse-recovery losses in these devices. SiC FETs do suffer from reverse-recovery losses because of the body diode in their structure. A typical SiC FET has greater than 85 nC of reverse-recovery charge.
- **Lower switching energy.** GaN's switching energy is more than 50% lower than SiC, which directly translates to lower losses in the PFC stage. It is possible to achieve switching frequencies greater than 1 MHz in critical model totem-pole applications.
- **Faster switching speeds.** New generations of GaN devices with integrated gate drivers can switch at up to 150 V/ns, resulting in an 82% reduction in losses compared to SiC and 63% compared to discrete GaN FETs.
- **Lower dead-time losses.** During PFC operation, there is a short period in each switching cycle—also known as the dead time—where neither switch in the half bridge is turned on. The duration of the dead-time period and associated voltage and current will result in losses in each cycle. A complex control algorithm such as adaptive dead time can help lower these losses. The availability of advanced driver features, such as the ideal-diode mode, make it possible to lower dead-time losses by more than 67% compared to both SiC and discrete GaN implementations without the need for complex firmware or hardware control.

Figure 3 provides a detailed loss breakdown between a dual-boost PFC, a totem pole with SiC and a totem pole with GaN. GaN offers the lowest losses and the highest efficiency in this application. These advantages not only enable designers to realize high power density, but also significantly reduce the cost and size of cooling components such as heat sinks and fans.

Figure 2. Dual boost PFC vs. totem-pole PFC

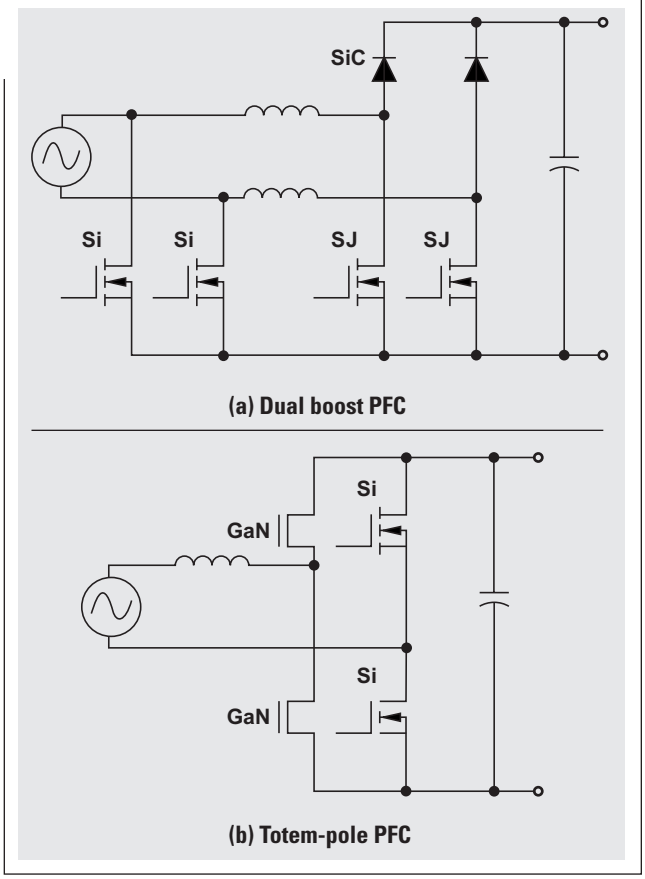
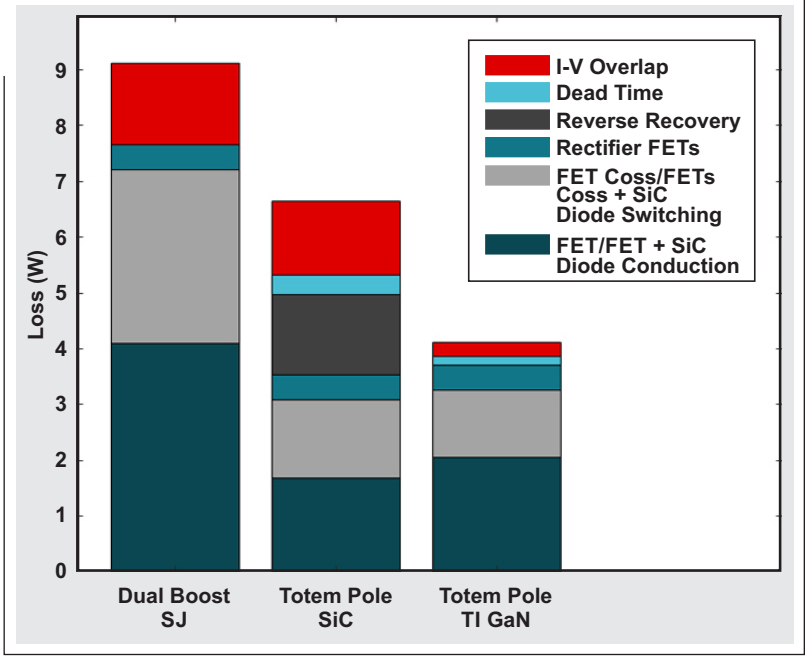


Figure 3. 1-kW PFC loss breakdown comparison between superjunction (SJ), SiC and GaN



Three-phase grid converters

In contrast to single-phase PFC applications, power supplies tied to a three-phase grid typically operate at much higher AC and DC bus voltage levels. AC inputs are typically 480 V line-to-line and depending on the application, the DC bus voltage could be 900 V or higher. Although a two-level converter 600-V GaN FET is not an option, multilevel topologies, using TI GaN for instance, do offer a viable alternative. Multilevel circuits use various configurations of lower-voltage device stacking and control to enable higher-voltage three-phase grid applications.

In contrast to a two-level converter with a 1,200-V SiC or IGBT, GaN (as shown in Figure 4) has some advantages in multilevel converter applications, including:

- **Superior switching figures of merit (FOMs).** As described earlier, GaN offers advantages over SiC in terms of reverse recovery, switching energy and speed, and dead-time losses. These advantages are even more prominent when comparing a 600-V GaN FET to a 1,200-V SiC or IGBT.
- **Lower system costs.** This includes manufacturing costs, reduced through the use of surface-mount devices, and also significantly reduced electromagnetic interference components, magnetic filter sizes and cooling.
- **Better thermal distribution.** This is particularly important in applications using convection cooling and enables designers to spread the thermal energy across a larger number of power devices.
- **Higher system density.** Because of the higher switching frequency of these converters, it is possible to achieve significant savings in the size of passives as well as heat sinks throughout the system.

Table 1 summarizes the advantages of GaN in multilevel grid converters.

Table 1. Comparing IGBTs, SIC and TI GaN devices for multilevel converters

Typical Operating Conditions	IGBT	SiC	TI GaN
Frequency (kHz)	20	100	140
Open-frame power density (W/in^3)	73	170	211
Efficiency (%)	98.3	98.9	99.2

GaN and SiC cost comparison

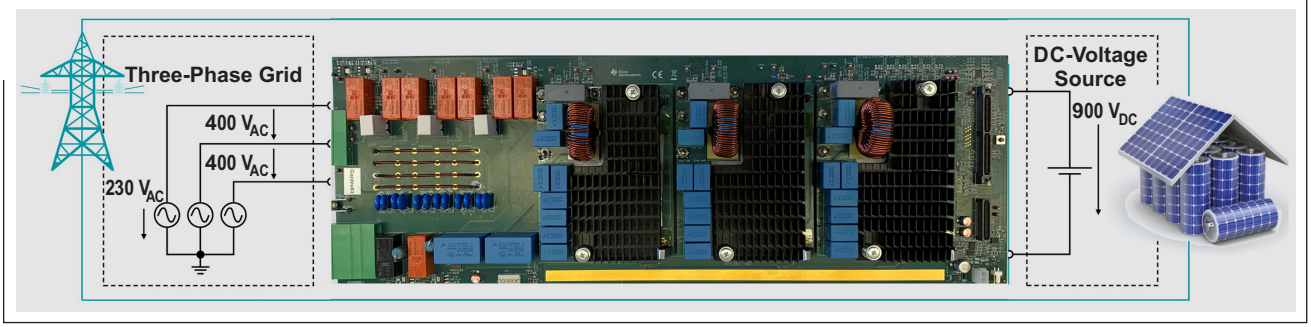
As mentioned earlier, GaN enables significant system-level cost savings by eliminating the number of active and passive components, enabling the use of smaller and lighter magnetics, and reducing the cooling needs in the system. However, these savings go much further. GaN is on a trajectory to provide the lowest device cost as well.

The cost of any semiconductor integrated circuit or field-effect transistor (FET) is the sum of several different parameters, regardless of device technology. These include:

- **Substrate cost.** The base starting material or wafer for a given technology.
- **Wafer fabrication.** The multistep process of building a semiconductor device on a wafer.
- **Depreciation.** The cost of capital amortized per device.
- **Chips per wafer.** The number of device die on a single wafer.
- **Package.** The materials and cost required to assemble a die into a final package.
- **Test.** The cost required to ensure that the final device meets data-sheet specifications.
- **Yield.** The overall device yield during the manufacturing process.

To simplify the discussion, it is possible to remove the package, test and yield items from the list above, as they

Figure 4. 900-V, 5-kW bidirectional AC/DC converter with TI GaN



are similar for most power semiconductor devices in the long run. For now, depreciation is also left out, which just leaves the costs associated with substrate, fabrication and number of chips per wafer to determine the differences in cost entitlement between GaN and SiC and expressed by Equation 1:

$$\text{Device cost} = \frac{\text{substrate} + \text{fabrication}}{\text{chips per wafer}} \quad (1)$$

The number of chips per wafer is a function of various factors including wafer size, device $R_{DS(on)}$ and thermal resistivity of a given technology. SiC typically has better thermal resistivity than both GaN and silicon, and as such, yields a higher number of chips per wafer. However, this is only one part of the total cost calculation.

Substrate cost is a major differentiator between GaN and SiC. GaN devices are grown on standard and readily available silicon substrates, similar to how billions of semiconductor integrated circuits are made every year. Also, being on silicon substrate, manufacturers can leverage existing fabrication and tools, including the path to 300-mm wafers.

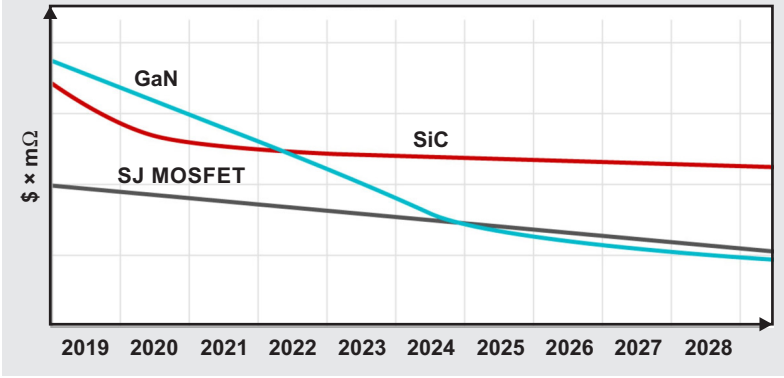
SiC not only has a significantly higher raw material cost but also requires specialized processes for manufacturing. One key aspect of the SiC manufacturing process is the need for temperatures in excess of 2,500°C, which incurs high energy costs for manufacturers. Table 2 estimates normalized substrate and fabrication costs of high-voltage power devices.

Table 2. Normalized future device costs of power devices

Technology	Normalized Substrate and Fabrication	Normalized Chips per Wafer	Normalized Device Cost
Superjunction (SJ) MOSFET	1.0	1.0	1.0
GaN	3.0	2.4	1.3
SiC	10.3	4.3	2.4

Depreciation was left out to simplify the cost analysis. However, depreciation becomes critical when projecting cost trends and comparing SJ MOSFETs, SiC and GaN. These devices are in different stages of maturation and have different depreciation models. In fact, GaN provides the highest cost-saving opportunity going forward. Strong market adoption increases fabrication utilization and speeds up capital depreciation, and thus lowers the total cost over time. Figure 5 compares the projected cost trends of the three technologies.

Figure 5. Relative cost projection by FET technology



Conclusion

The invention of MOSFET transistors revolutionized the world of power electronics and enabled engineers to do things never before possible. Years later, the commercialization of wide-bandgap GaN and SiC devices once again made the impossible a reality.

SiC and GaN serve different voltage, power and application needs, but they also overlap in some end equipment. SiC devices offer voltage levels as high as 1,200 V with high current-carrying capabilities. This makes them a good fit for applications such as automotive and locomotive traction inverters, high-power solar farms and large three-phase grid converters. On the other hand, with its superior switching FOM, inherent manufacturing and cost advantages and ability to switch at much higher frequencies, GaN has become the device of choice for many designers in <10-kW applications. Whether the product is a USB Type-C® adapter, a multikilowatt telecom rectifier, an integrated robotics motor drive or an electric vehicle onboard charger, designers finally have tools that enables them to make the best choice when designing greener, lighter and more cost-effective products.

Related Web site

Product information:
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