Silicon carbide gate drivers – a disruptive technology in power electronics

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Introduction

Preventing global warming has made carbon dioxide (CO_2) emissions reduction a strong focus worldwide. Emissions reduction, in combination with reducing fossil-fuel use as an energy source, has led to several disruptive behaviors in applications we use every day. The trend is now toward energy-efficient, robust and compact systems. Economically, this also translates into energy savings for consumers.

For example, automakers have committed to developing and selling hybrid electric vehicles/ electric vehicles (HEVs/EVs), which are expected to reach 8 million units by 2021 [1]. Industrial high-power products such as motor drives, solar inverters and servers for data centers are also moving toward achieving higher system efficiency, longer lifetimes and more compact solutions to realize carbon-reduction goals.

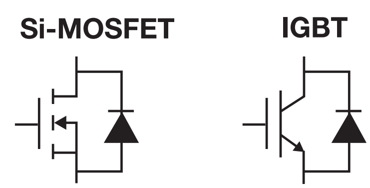
Power electronics – and thus power semiconductor devices – play a critical role in meeting these demanding requirements by realizing these attributes:

- Lower power loss
- High-frequency operation
- Higher junction temperatures
- High-voltage operation
- Increased heat dissipation

This paper will examine the value of silicon carbide (SiC) as a power semiconductor switch and its ecosystem – particularly the gate driver – to realize CO_2 emissions reduction and its associated benefits. I will also discuss gate-driver and isolation requirements.

The current climate for high-power semiconductor selection

Silicon-based power semiconductor switches have traditionally been and still are the primary choice for high-power application designers, who typically make this choice based on voltage and power ratings. **Figure 1** shows two popular silicon-based power semiconductors based on voltage requirements for high-voltage applications: metal-oxide semiconductor field-effect transistors (MOSFETs) and insulated gate bipolar transistors (IGBTs).



Voltage Ratings	20~650V	≥650V
Optimal V_{GS} Max. Limit	0~15V (±20V)	-10~15V (-10~20V)

Figure 1. *Popular silicon-based power semiconductors based on voltage ratings.*

Applications that require bus voltages greater than 400 V – such as EVs, motor drives and string inverters [2], [3] – require power semiconductor switches with voltage ratings greater than 650 V. Furthermore, such applications are high-power solutions (in the range of a few kilowatts to 1 MW).

You can currently use IGBTs for power electronics switching up to 1,200 V. Several applications are moving toward even higher voltages, where current ratings are expected to be lower, with reduced conduction losses. Some of these applications warrant voltages beyond 1,200 V – up to 1,700 V – such as multiphase motor drives.

Why SiC?

To realize CO_2 emissions reduction, as I mentioned earlier, there is a strong push toward higher system efficiency, longer lifetimes and more compact solutions. Unfortunately, MOSFETs and IGBTs are approaching their theoretical limits. IGBTs currently used in high-voltage (>650 V)/high-power applications are already being stretched to their absolute limit at voltages above 1 kV.

SiC FETs have emerged as a disruptive material due to their superior material properties, including low on resistance, high thermal conductivity, high breakdown voltage and high saturation velocity compared to silicon, as illustrated in **Table 1**.

Property	Definition	Si	SiC-4H
E_G (eV)	Bandgap Energy	1.12	3.26
E_{BR} (MV/cm)	Critical Field Breakdown Voltage	0.3	3.0
v_S (x107cm/s)	Saturation Velocity	1.0	2.2
μ (cm^2/V.s)	Electron Mobility	1400	900
λ (W / cm.K)	Thermal Conductivity	1.3	3.7

Table 1. *The intrinsic material properties of SiC.*

SiC has a breakdown voltage 10 times higher than silicon, resulting in a lower on resistance compared to silicon – and thus realizing high-voltage operation with low conduction losses. SiC has a bandgap energy three times higher than silicon, enabling system operation at higher junction temperatures. Whereas silicon-based power devices operate at a junction temperature (Tj) of 150°C, the higher Tj of SiC (greater than 200°C) means that systems can operate in environments that achieve ambient temperatures of 175°C or more. One example of such an environment would be power converters located under the hood of an HEV.

The high saturation velocity and electron mobility of SiC lowers switching losses and enables higher system operating frequencies. In turn, these benefits lead to a reduction in passive elements and therefore the size and the weight of the system. SiC has three times the thermal conductivity of silicon, enabling systems with fewer cooling needs.

All of these characteristics result in an energy-efficient, robust and compact system. **Figure 2** shows the value of the material properties of SiC and their corresponding system benefits.

Going back to automotive applications, compact systems enable easier integration of power electronics into traction motors, resulting in an overall weight and size reduction in HEVs/EVs. This, along with increased efficiency and robust

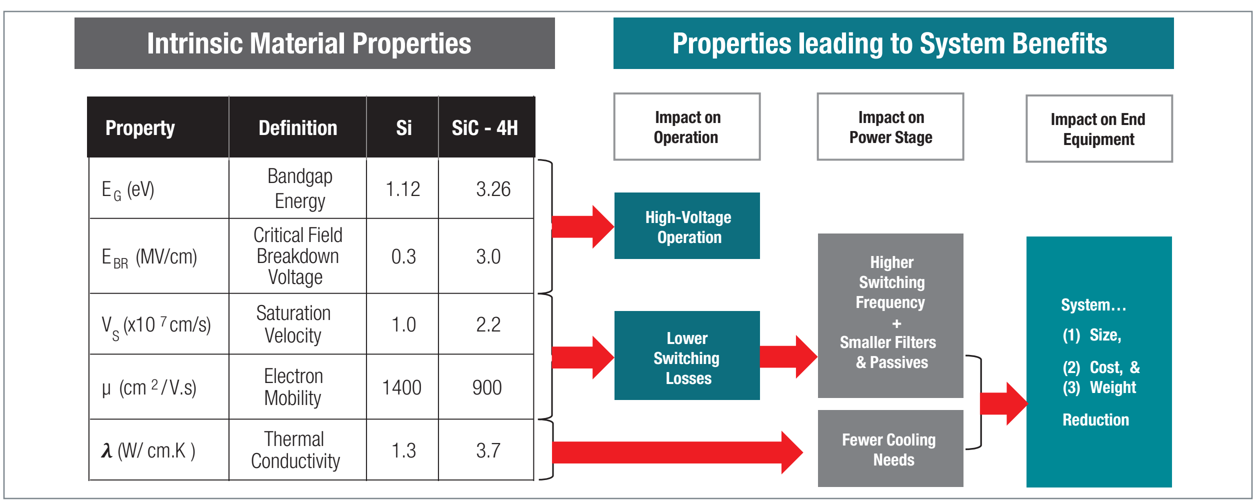


Figure 2. *Material properties of SiC impacting system benefits.*

characteristics, significantly improve mileage ranges and therefore bring more energy savings to consumers.

Gate drivers in the SiC ecosystem

At a system level, there are ideally three semiconductor components for high-power solutions like traction inverters, drives and solar inverters: the controller, gate driver and power semiconductor (SiC in this case). It is therefore important to understand how to drive SiC power devices. These switches turn on and off for efficient power transfer across the power-electronics circuit, as dictated by the controller.

A key element that acts as an interface between the controller and power device is the gate driver. Think of it as an amplifier that takes the controller signal and amplifies it to drive the power device. Given the superior characteristics of SiC FETs, defining the requirements for gate drivers becomes very critical. They are:

- A high supply voltage of 25-30 V, to realize high efficiency through low conduction losses
- A high drive strength (typically greater than 5 A), to realize low switching losses
- Fast short-circuit protection, for fast responses due to SiC switching faster relative to silicon-based power switches (MOSFETs and IGBTs)
- Smaller propagation delay and variation, for high efficiency and fast system control
- High dv/dt immunity, for robust operation

These requirements are unique for SiC versus silicon-based MOSFET and IGBT gate drivers, as shown in **Table 2**.

One unique feature for a SiC gate driver is fast overcurrent protection, versus desaturation for an IGBT gate driver. For the same rated current and voltage, IGBT reaches the active region for significantly lower voltage between the collector

Power Switch	Si MOSFET	Si IGBT	SiC
Switching Frequencies	High (>20 kHz)	Low to Medium (5-20kHz)	High (>50 kHz)
Basic Protection	No	Yes – Desaturation, Miller Clamping	Yes – Current sense, Miller Clamping
Max. V_{DD} (power supply)	20V	30V	30V
V_{DD} Range	0-20V	-10 to 20V	-5 to 25V
Operating V_{DD}	10-12V	12-15V	15-18V
UVLO	8V	12V	12-15V
CMTI	50-100V/ns	<50V/ns	>100V/ns
Propagation Delay	Smaller the better (<50ns)	High (not critical)	Smaller the better (<50ns)
Rail Voltage	Up to 650V	>650V	>650V
Typical Applications	Power supplies – Server, datacom, telecom, factory automation, onboard and offboard chargers, solar u-inverters and string inverters (<3kW), 400-12V DC/DC – Auto	Motor drives (AC machines), UPS, solar central and string power inverters (>3kW), traction inverters for auto	PFC – Power supplies, solar inverters, DC/DC for EV/HEV and traction inverters for EV, motor drives, railways

Table 2. *Comparing SiC to MOSFET and IGBT gate drivers.*

and emitter (V_{CE}) (typically 9 V) compared to a SiC MOSFET. IGBT self-limits the current increase. In the case of SiC, the drain current ID continues to increase with an increase in the drain-to-source voltage difference (V_{DS}), eventually resulting in faster breakdown, as illustrated in **Figure 3**. It is therefore critical for a SiC gate driver to have fast protection and therefore fast fault reporting, typically 400ns.

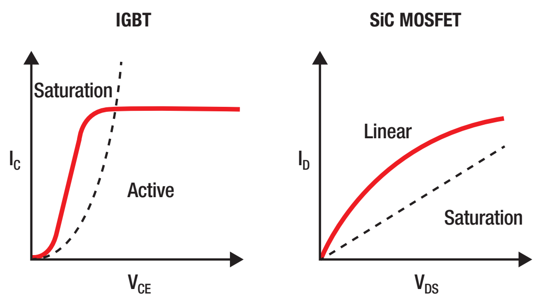


Figure 3. *Differences in current-voltage (I-V) characteristics between a SiC MOSFET and IGBT.*

The gate voltage must have a high dv/dt in order to accommodate the high switching speeds of SiC, thus necessitating a low-impedance driver for robust operation.

Since SiC is used in high-voltage/high-power applications, and since there is a human machine interface (HMI) involved, almost all gate drivers for SiC are isolated.

The need for digital isolation

Galvanic isolation is a technique that isolates functional sections of electrical systems to prevent the flow of direct current or uncontrolled transient current between them. Data and energy still need to pass through galvanic isolation barriers, however. This barrier is based on optical, magnetic or capacitive isolation technologies. Of these, capacitive and magnetic isolation are digital isolators where data transmits through the barrier digitally. Like magnetic isolation, capacitive isolation has digital circuits for encoding and decoding incoming signals so that they can pass through the isolation barrier.

Fundamentally, capacitors can only pass AC signals, not DC signals; plus, they are not susceptible to magnetic noise while maintaining high data rates and keeping power consumption low. This makes capacitive isolation the right choice for SiC gate drivers because of their high data rates and high noise immunity (with common-mode transient immunity above 150 V/ns).

TI recently introduced the industry's first family of isolated gate drivers, UCC217xx, with fast, integrated sensing for IGBTs and SiC MOSFETs. This family of devices provides advanced monitoring and protection while improving total system efficiency in automotive and industrial applications such as traction inverters, on-board chargers, drives and high power conditioners in grid-tied systems. With integrated components, these devices provide fast detection time to protect against overcurrent events while ensuring safe system shutdown. Utilizing capacitive isolation technology, the UCC217xx family maximizes insulation barrier lifetimes while providing high reinforced isolation ratings, fast data speeds and high density packaging. This family amplifies the value of the systems using SiC MOSFETs listed below:

- **Enhanced system performance**: The devices' high-peak drive strength of ±10 A maximize switching behavior and reduce losses, while 200 ns of overcurrent detection enables fast system protection.
- **Strengthened system-level reliability:** The UCC217xx family extends insulation barrier lifetimes with capacitive isolation technology and industry-leading, reinforced isolation ratings with surge immunity up to 12.8 kV. Additionally, the devices ensure accurate data communication with common-mode transient immunity (CMTI) of >150 V/ns.
- **Reduced system size:** The gate drivers eliminate external components with integrated buffers and sensors while providing accurate temperature,

current or voltage sensing, with an isolated analog-to-pulse-width modulation sensor to simplify system-level diagnostics and prevent switch failures.

System-level advantages and challenges

SiC FETs can switch faster than IGBTs because of the absence of a tail current during SiC turn-off. However, this tail current provides a method to dampen any ringing during turn-off, which is actually an advantage in IGBTs (especially in motor-drive applications) because any false turn-on and thus overshoot could damage the system. The challenge at the system level for SiC-based applications is to control ringing through gate resistors or snubbers.

Higher switching speeds imply smaller magnetic and capacitor filter sizes, thereby reducing system size and cost. As I mentioned earlier, the system should also have fewer cooling needs given the high thermal conductivity.

Some system-solution suppliers still argue that reducing the system size and cost are not sufficient to negate SiC's high component cost. Since SiC-based system development is still at an early stage, the cost will be high for now. With more market adoption, however, it is only natural that SiC costs will come down due to economy of scale, thus realizing the cost benefits at the system level.

Summary

To achieve CO_2 emissions reduction mandates, high-power density, robust and compact solutions are becoming a trend in high-power applications such as traction inverters, onboard chargers, solar inverters and motor drives. SiC has emerged as a disruptive material that has superior material properties compared to silicon, including low on resistance, high thermal conductivity, high breakdown voltage and high saturation velocity. The uniqueness of the gate driver for SiC FETs is a key component in a SiC ecosystem, but given high voltages and high power levels, it is important to protect the HMI and intelligent systems. Therefore, isolated gate drivers are becoming the norm for SiC gate drivers.

TI offers several SiC isolated gate drivers for power switches, including the UCC217xx, UCC21521C, UCC53xx and ISO545x/585x families.

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