Silicon Carbide Gate Drivers – A Disruptive Technology In Power Electronics

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. Applications that require bus voltages greater than 400V – such as EVs, motor drives and string inverters require switches with voltage ratings greater than 650 V. Unfortunately, MOSFETs and IGBTs are approaching their theoretical limits. IGBTs currently used in high-voltage (>650V)/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 properties. This article examines the value of SiC as a switch and its ecosystem – particularly the gate driver. **Nagarajan Sridhar, Strategic Marketing Manager – SiC and Smart Isolated Drivers, Texas Instruments, Dallas, USA**

SiC has a breakdown voltage 10 times higher than Silicon, resulting in a lower on resistance – 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 (T_j) of 150°C, the higher T_j 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.

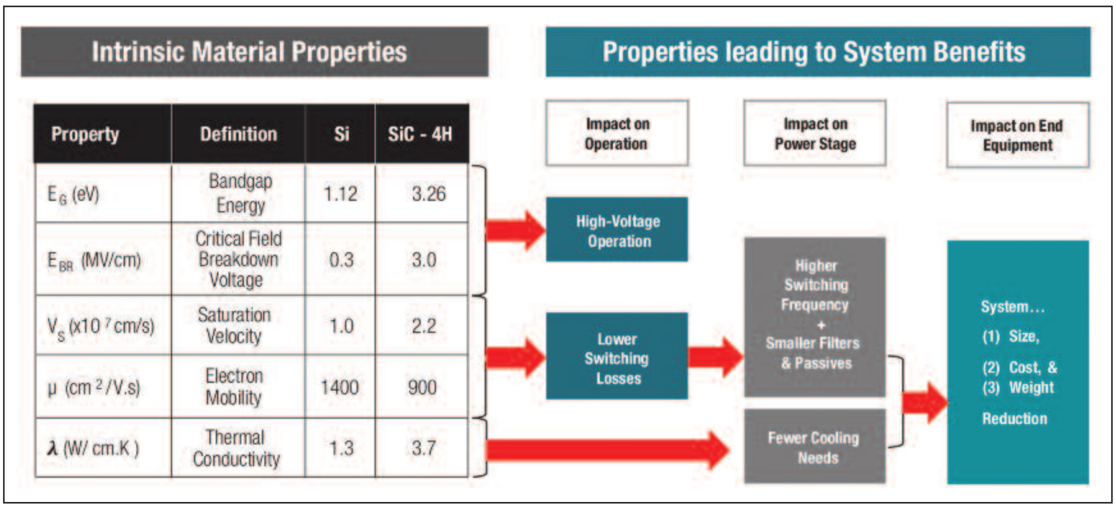
All of these characteristics result in an energy-efficient, robust and compact system. Figure 1 shows the value of the material properties of SiC and their corresponding system benefits. Going back to automotive applications, compact systems enable easier integration of power electronics into traction motors, resulting in an overall weight and size reduction in HEVs/Evs. This, along with increased efficiency and robust ranges and therefore bring more energy savings.

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.

These requirements are:

- A high supply voltage of 25-30V, to realize high efficiency through low conduction losses



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 (x10 ^{7} cm/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

Figure 1: Material properties of SiC impacting system benefits

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 1: Comparing SiC to MOSFET and IGBT gate drivers

- A high drive strength (typically greater than 5 A), to realize low switching losses
- Fast short-circuit protection for fast responses
- 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 1. One unique feature for a SiC gate driver is fast over-current 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 and emitter (V_{CE}) at typically 9 V compared to a SiC MOSFET. IGBT self-limits the current increase. In the case of SiC, the drain current I_D continues to increase with an increase in the drain-to-source voltage difference (V_{DS}), eventually resulting in faster breakdown, as illustrated in Figure 2. It is therefore critical for a SiC gate driver to have fast protection and therefore fast fault reporting, typically 400 ns. 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.

The need for digital isolation

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.

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).

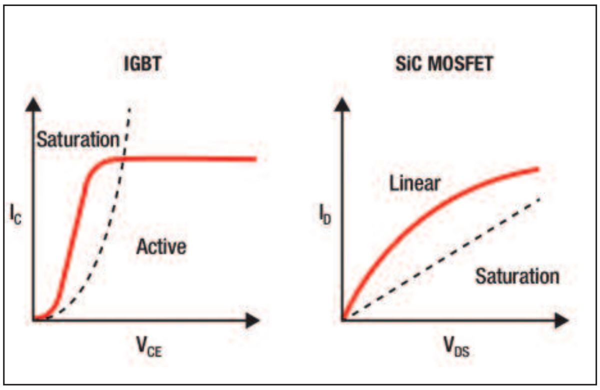


Figure 2: Differences in current-voltage (I-V) characteristics between a SiC MOSFET and IGBT

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 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.

Conclusions

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 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 UCC21521C, UCC53xx and ISO545x/585x families.