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Overview of Silicon Carbide Power Devices

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Abstract: Silicon (Si) is by far the most widely used semiconductor material for power devices. However, Si-based power devices are approaching their material limits, which has prompted a lot of efforts to find alternatives to Si-based power devices for better performance. With the rapid innovations and developments in the semiconductor industry, Silicon Carbide (SiC) power devices have evolved from immature prototypes in laboratories to a viable alternative to Si-based power devices in high-efficiency and high-power density applications. SiC devices have several compelling advantages—high-breakdown voltage, high-operating electric field, high-operating temperature, high-switching frequency and low losses. Even though the price of SiC devices is still higher than its Si counterparts, SiC devices are finding more applications where the benefits of SiC technology can offer system advantages, which are significant enough to offset the increased device cost. Even though several SiC-based power devices have been successfully commercialized recently, the SiC device market is still in its early stage and its potential users (power supply designers) are not familiar with this new technology. In this article, the pros and cons of commercially available SiC power devices will be discussed along with a comparison to their Si counterparts to help power supply designers learn more about this new technology and select the right SiC devices suitable for their applications.

Introduction: Power semiconductor devices constitute the heart of power electronics systems, and silicon (Si)-based power devices have been the dominant choice for this system. However, as the needs and requirements for electrical energy continuously grow, Si-based power devices have limited performance related to inherent material characteristics, which make them unable to meet future demands, especially in high-voltage, high-efficiency, and high-power density applications[1]-[2]. SiC has become the material of choice for next generation power semiconductor devices to replace existing Si technology. The wider bandgap, higher thermal conductivity, and larger critical electric field allow SiC devices to operate at higher temperatures, higher current density, and higher blocking voltages than Si power devices.

Silicon carbide is comprised of equal parts silicon and carbon via covalent bonding. Since this process will lead to a highly ordered configuration, a single crystal SiC is extremely hard; in fact it is known to be the third hardest substance on earth. There are more than 170 different polytypes. Depending on the polytype crystal structure, the energy gap of silicon carbide varies from 2.2 to 3.3 eV. Among them, 4H and 6H are of interest technologically since large wafers can be made in this material, and hence used for device production. Table I summarizes the characteristics of 4H and 6H SiC devices in comparison with Si devices. As observed in Table I, the wide band gap energy of SiC results in a number of favorable characteristics for power electronics devices.

- **Higher critical electrical field:** The critical electrical field of SiC is around 8 times higher than that of Si, which makes SiC an excellent choice for power semiconductor devices. A SiC semiconductor die is much thinner due to its high dielectric strength and is doped to a much higher level, leading to lower losses.
- **Higher thermal conductivity:** SiC has thermal conductivity about 3 times higher than that of silicon. Therefore, heat dissipation by the losses can be conducted from within the semiconductor with a much lower temperature drop across the semiconductor material.

- **Higher operating temperature:** Because of its high melting temperature, the SiC device can operate well over 400°C—much higher than the maximum allowable junction temperature of standard silicon technology (150°C). This property results in significant cost reduction of the cooling system since less expensive cooling materials and methods can be used. Even in the extremely high ambient temperature, enough temperature differential can be obtained to take the heat out of the semiconductor package. The ambient air temperature can be as high as 100°C without any concern.

- **Higher current density:** The current density of SiC is 2 to 3 times the maximum current density of silicon devices. This property will reduce cost and will, over time, help to offset some of the cost disadvantages of the SiC device.

Table I. Characteristics of SiC Devices Versus Si Devices

Electrical Property	Si	SiC (4H)	SiC (6H)	Diamond
Band Gap Energy (eV)	1.12	3.28	2.96	5.5
Critical Electrical Field (MV/cm)	0.29	2.5	3.2	20
Electron Mobility (cm^2/VS)	1200	800	370	2200
Hole Mobility (cm^2/VS)	490	115	90	1800
Thermal Conductivity (W/cmK)	1.5	3.8	3.8	20
Maximum Junction Temperature (°C)	150	600	600	1927

Even though several SiC-based power devices have been successfully commercialized, the SiC device market is still in an early stage. Today, the only commercially available SiC power devices are Schottky diodes, JFETs, MOSFETs and BJTs. For SiC switches in particular, the drivers still remain challenging. In the next section, the pros and cons of each commercially available SiC power devices will be discussed along with a comparison of their Si counterparts.

Review of Commercially Available SiC Power Devices

SiC Schottky Diode: The SiC Schottky diode is the first successfully commercialized SiC power device. Schottky diodes are majority carrier devices, and they do not have reverse recovery phenomena—a very favorable characteristic for high-voltage applications. The SiC technology extended the breakdown voltage of a Schottky diode above 1000 V, which had been limited below 200 V with Si technology. Table II summarizes the key characteristics of the SiC Schottky diode (Infineon-IDW15S120).[3] Due to the wide band-gap energy, the forward voltage drop of the SiC Schottky diode is 1~2 V, which is larger than its Si counterpart. Thus, the main advantage of SiC Schottky diode is obtained in high-voltage applications where the larger voltage drop has negligible impact on the losses. Another important characteristic of the SiC Schottky diode that is the opposite of its Si counterpart is that the forward voltage drop has positive thermal coefficient (increases as temperature increases), which allows parallel connection of the Schottky diode to handle higher current. Since the forward voltage drop of the SiC Schottky diode at 150°C is almost double compared to that of room temperature, the heatsink for SiC Schottky diode should be designed with enough margin to avoid thermal runaway.

Table II. Characteristics of SiC Schottky Diode (Infineon-IDW15S120)

Parameter	Value			Unit	Test Condition
	Min.	Typ.	Max.		
Continuous Forward Current	–	–	15	A	T_C <135°C
Repetitive Peak Reverse Voltage	1200	–	–	V	20
Operating Temperature	–55		175	°C	5.7
Diode Forward Voltage	–	1.5	1.8	V	I_F = 15A, T_J = 25°C
		2.4		V	I_F = 15A, T_J = 150°C

SiC JFET: The SiC JFET was commercialized earlier than other SiC switches since it is relatively easy to implement and there is no reliability issue of the gate oxide as observed in SiC MOSFETs. Basically, the JFET is normally an ON-type switch, as illustrated in Figure 1, which can be implemented with vertical or horizontal trench structure. The normally ON-type JFET is also called depletion mode JFET and fully turned off when the gate voltage is below the pinch-off voltage (about -15 V). When turned on, it exhibits constant ON-resistance which can be minimized when the gate voltage is slightly higher than zero as shown in Figure 1.

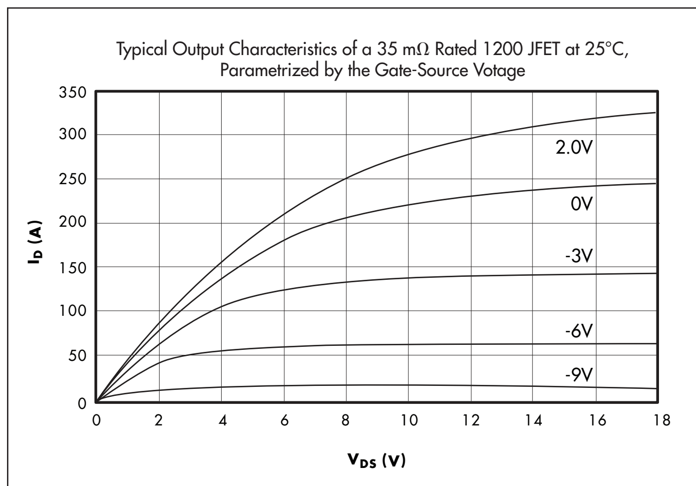

Figure 1. Typical I_D vs. V_{DS} for different gate voltage of Normally ON type JFET

The normally-ON characteristic definitely is controversial since the loss of control can cause undesired conduction of the switches and consequently can lead to shoot through current damaging the power system. One common technique to address this issue is to use a cascode driver, as shown in Figure 2, where a low-voltage, high-current Si MOSFET is connected to the source of SiC JFET. Typically 30 V MOSFETs with several mΩ ON-resistance are used for the cascode configuration. During normal operation, the low-voltage MOSFET is conducting without significant contribution to the total ON state resistance. In case of start-up and malfunction, the normally-OFF MOSFET is turned off pushing the source of the JFET to a positive potential relative to its gate and hence turning the JFET into a safe OFF-state. In normal operation, the JFET is driven by the Si MOSFET gate. When the Si MOSFET is turned on, the gate voltage of JFET becomes zero allowing the conduction of the JFET. Another driving method for the cascode circuit is to guarantee the MOSFET to be always turned on as long as the driver power supply is present (Direct driving[4]). Then, the circuit acts like a stand-alone JFET in normal operation, which avoids the switching loss related to the MOSFET and the limitations of a conventional cascode circuit caused by switching timing.

It is also possible to allow the FET to have a normally-OFF characteristic by adjusting the thickness of the vertical channel and doping level when vertical trench structure is used. The normally OFF type of JFET is also called enhancement mode JFET and remains in the OFF state when the gate voltage is zero and is fully turned on when the gate voltage is around 2~3 V. However, this type has typically larger specific resistance than the normally OFF type of JFET, and therefore will not be discussed in detail in this paper.

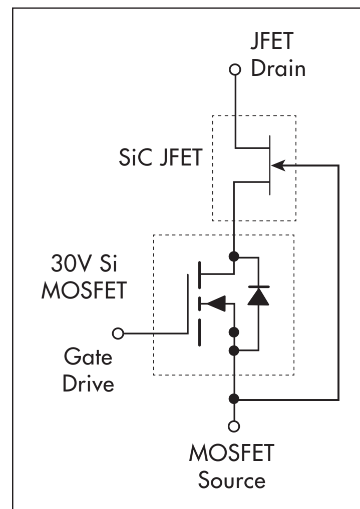

Figure 2. Conventional Cascode Drive Circuit

SiC MOSFET: The SiC MOSFET is being commercialized later than the SiC JFET since SiC MOSFETs have traditionally suffered from poor oxide-semiconductor interface quality, which has led to large threshold voltage instability. The gate oxide also degrades at a temperature even below maximum junction temperature of a SiC device. However, the SiC MOSFET is still an attractive device since it is voltage controlled and normally an OFF type of device which does not require continuous driving current to maintain the conduction state. Compared to a Si MOSFET, SiC MOSFETs have very unique operating characteristics that should be considered when designing the gate drive circuit. As can be seen in Figure 3, the transition from

linear (ohmic) to saturation regions is not clearly defined as its Si counterpart exhibits, which is caused by the low transconductance of the SiC MOSFET. Figure 4 demonstrates how the nominal threshold voltage is around 2.5 V, and the device is not fully on until the V_{GS} is above 16 V. Thus, the recommended ON-state V_{GS} is 20 V for its full performance, whereas the recommended off-state V_{GS} is between -2 V to -5 V since the V_{GS} threshold has a low noise margin.

Table III shows key parameters of a SiC MOSFET (CREE-CMF20120D).[5] Notice that the temperature coefficient of the ON resistance of the SiC JFET is smaller than that of the Si MOSFET. The ON-resistance of the SiC MOSFET increases by about 20 percent when the junction temperature increases from 25°C to 135°C, whereas that of the Si MOSFET increases by 250 percent—an advantage that resulted from the wide bandgap. Another important temperature related characteristic is that the zero gate leakage current of the SiC MOSFET does not rise much with temperature, whereas that of its Si counterpart increases around 100 times when the junction temperature increases from 25°C to 135°C. The body diode of the SiC MOSFET is a PN diode that has 3.5 V forward voltage drop, about 5 times that of a Si PN junction diode. However, reverse recovery time is much smaller compared to a Si PN diode.

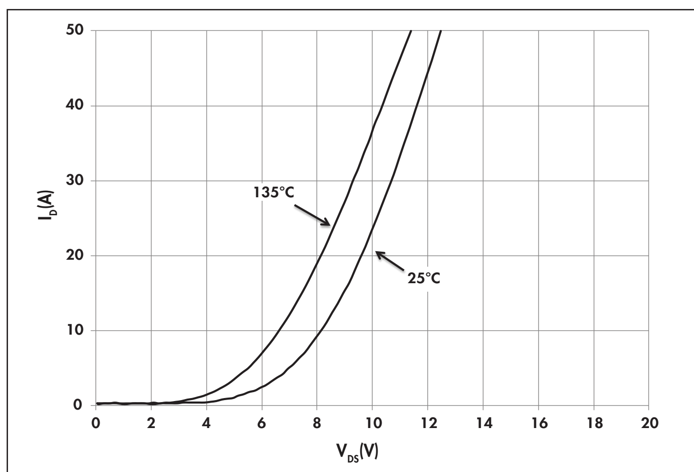

Figure 3. I_D vs. V_{DS} for different gate voltage of SiC MOSFET (CREE-CMF20120D)

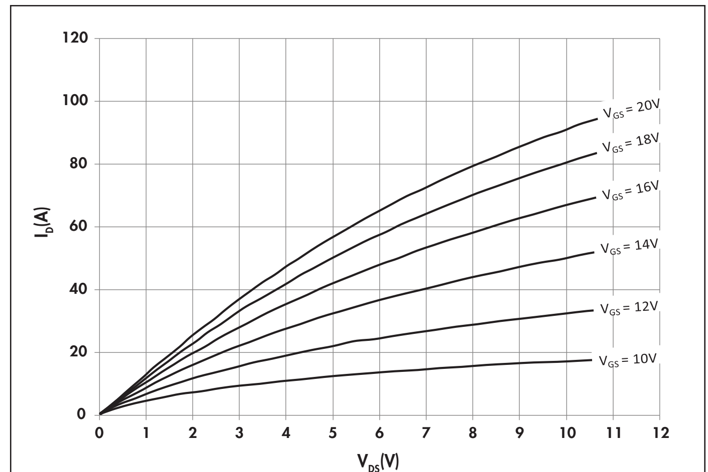

Figure 4. Typical Transfer Characteristics of SiC MOSFET (CREE-CMF20120D)

Table III. Characteristics of SiC MOSFET (CREE-CMF20120D)

Parameter	Value			Unit	Test Condition
	Min.	Typ.	Max.		
Gate Threshold Voltage	–	2.65	4	V	$V_{DS} = V_{GS}$, I_D = 1mA, T_J = 25°C
	–	3.2	4.8	V	$V_{DS} = V_{GS}$, I_D = 10mA, T_J = 25°C
	–	2.0	–	V	$V_{DS} = V_{GS}$, I_D = 10mA, T_J = 135°C
	–	2.45	–	V	$V_{DS} = V_{GS}$, I_D = 10mA, T_J = 135°C
Zero Gate Voltage Drain Current		1	100	μA	V_{DS} = 1200V, V_{GS} = 0V, T_J = 25°C
		10	250	μA	V_{DS} = 1200V, V_{GS} = 0V, T_J = 135°C
Drain-to-Source ON-State Resistance		80	100	mΩ	V_{GS} = 20V, I_D = 20A, T_J = 25°C
	–	95	120		V_{GS} = 20V, I_D = 20A, T_J = 135°C
Diode Forward Voltage of Body Diode		3.5		V	V_{GS} = -5V, I_F = 5A, T_J = 25°C
		3.1			V_{GS} = -5V, I_F = 5A, T_J = 135°C
Reverse Recovery Time of Body Diode		138		ns	V_{GS} = -5V, I_F = 10A, T_J = 25°C

SiC BJT: Theoretically, the SiC BJT can provide the lowest specific ON-resistance that results in the smallest chip size parasitic capacitance for a given voltage and current rating, allowing higher switching speed than other SiC

switching devices. Its short circuit capability and absence of second breakdown also make the SiC BJT more reliable than other SiC switches. The SiC BJT has no oxide layer and can operate at higher temperatures than the SiC MOSFET.

Since it is a current controlled device, a certain amount of drive current is required to maintain the ON status. The high current gain can be obtained by heavily doping the concentration of the emitter above the doping concentration of the base and maintaining the base width in the range of the diffusion length. The SiC BJT commercialized by Fairchild Semiconductor has high current gain of around 50~70 in room temperature.[6] Figure 5 shows the I-V characteristics of the SiC BJT at room temperature. In the saturation region, the SiC BJT exhibits ohmic region property as the Si MOSFET does. Since it has a positive thermal coefficient, SiC BJTs can be paralleled to handle high current.

Table IV. Characteristics of SiC BJT

Parameter	Value			Unit	Test Condition
	Min.	Typ.	Max.		
Collector Cut-Off Current	–		100	μA	V_{CE} = 1200V, T_J = 25°C
	–		100	μA	V_{CE} = 1200V, T_J = 150°C
DC Current Gain	52				I_C = 10A, T_J = 25°C
	45				I_C = 50A, T_J = 150°C
Collector-Emitter Saturation Voltage			0.85	V	T_{ON} = 300μs, I_C = 50A, I_B = 2A, T_J = 25°C
	–		1.3	V	T_{ON} = 300μs, I_C = 50A, I_B = 2A, T_J = 150°C
Collector-Emitter ON-State Resistance			17	mΩ	T_{ON} = 300μs, I_C = 50A, I_B = 2A, T_J = 25°C
			26	mΩ	T_{ON} = 300μs, I_C = 50A, I_B = 2A, T_J = 150°C
Base-Emitter Saturation Voltage			3.5	V	T_{ON} = 300μs, I_C = 50A, I_B = 2A, T_J = 25°C
			3.4	V	T_{ON} = 300μs, I_C = 50A, I_B = 2A, T_J = 150°C

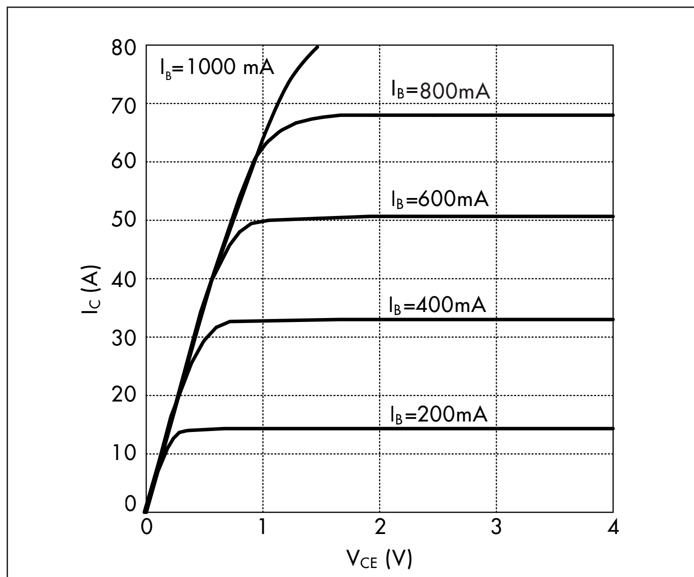

Figure 5. Typical I-V Characteristics of SiC BJT

As observed in Figure 6, parasitic capacitances exist on the base terminal. Thus, the switching performance of the device is determined by how quickly the charge can be moved in or out of the capacitances. The drive circuit also should provide DC-base current to maintain the conduction status.

Conclusion: This paper has examined the material characteristics of SiC that allow several compelling advantages

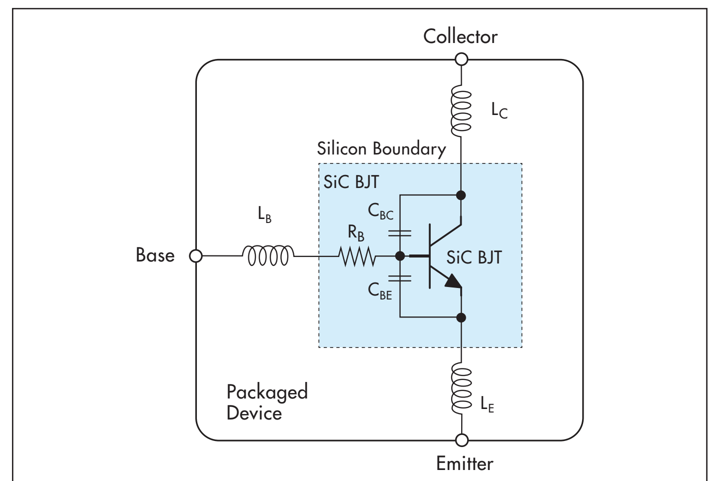

Figure 6. Equivalent circuit of SiC BJT

such as high breakdown voltage, high operating electric field, high operating temperature, high switching frequency and low losses. The benefits and limitations of each commercially available SiC power devices are discussed together with comparisons with their Si counterparts.

About the Author: Hangseok Choi received B.S., M.S., and Ph.D degrees in electrical engineering from Seoul National University in 1996, 1999, and 2002, respectively. From 2002 to 2007, he was a system and application engineer at Fairchild Semiconductor, Korea. Since 2008, he has been a principal system and application engineer at Fairchild Semiconductor in Bedford, NH, USA, where he is developing high-performance power management ICs. He has authored or coauthored more than 50 technical papers and holds 27 U.S. patents. His research interests include analysis, simulation, and design of high-frequency, high-power-density power converters.

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