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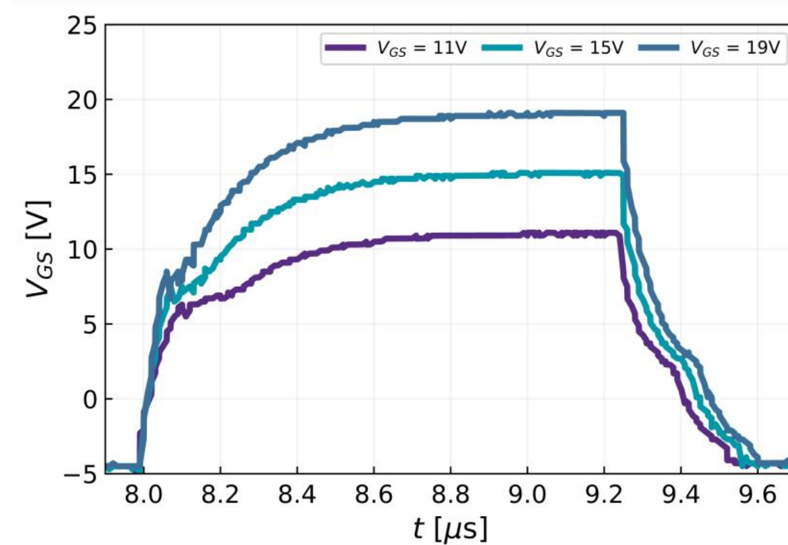
Application Note **PRD-08937**

Impact of V_{GS} on SiC MOSFET Characteristics



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SiC MOSFETs function well as power electronic devices used in hard-switching applications such as automotive drivetrain, motor drives, EV chargers and solar inverters. Achieving low switching losses while maintaining robust current capabilities, they are simple to incorporate into designs. As voltage-controlled devices, the SiC MOSFET's applied gate-source voltage, V_{GS}, can be tuned based on the application. This application note will discuss the benefits and drawbacks when changing V_{GS} and how it will influence the performance of the power system.

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1. Introduction

Power electronic systems are transitioning from traditional silicon (Si)-based devices (Si IGBT and Si power diode) to the more efficient silicon carbide (SiC) MOSFET. Thanks to the intrinsic nature of wide bandgap materials, SiC devices have higher breakdown voltage, can manage more current, function at higher temperatures, and offer faster switching speed with lower switching losses than Si devices [1]. This makes applications of the power MOSFET most useful for current control in inductive loads such as power train circuit design. One benefit of the MOSFET is the simplicity of device control. A simple switch is created with an on and off state that can be toggled by applying specific voltages. Typically, system level designers use a gate driver to control the on-state and off-state drive voltages. The recommended operational drive voltages will vary depending on the MOSFET manufacturer, so understanding how system design parameters vary with applied V_{GS} is important.

2. Background

Turn-On Transient

During a turn-on switching event, a constant positive voltage is applied across the gate-source terminals. A power MOSFET has several intrinsic capacitances that are charged during turn-on. The applied voltage creates a bias across the gate oxide of the device, creating a weak inversion that frees up a low concentration of free carriers and allows a small amount of current to flow. The gate to source capacitance, C_{GS}, is charged while $V_{GS} < V_{th}$. As soon as the gate voltage exceeds the threshold voltage ($V_{GS} > V_{th}$) of the device, the MOSFET enters the strong inversion domain of operation, freeing up a large concentration of free carriers and starting the conduction of current through the channel of the MOSFET. V_{GS} continues to rise until the Miller voltage is reached, V_{miller}, and the device enters the Miller plateau region which encompasses the time it takes to charge the gate to drain capacitance C_{GD}. During this time, in SiC devices, the dV_{GS}/dt decreases but is not zero and continues until the parasitic capacitance is fully charged. Finally, the device reaches the on-state drive voltage [2]. Increasing V_{GS} widens the inversion channel, leading to a larger concentration of free carriers permitting more current to flow and lowering the on-state resistance.

Turn-Off Transient

During turn-off, the applied voltage across the gate to source terminals is often negative (but sometimes zero for some industrial applications) for SiC devices. The off-state drive voltage indicates the voltage at which the device is held off, and a similar but inverted discharge effect takes place as compared to the turn-on. The first phase of turn-off occurs during the discharge of C_{DS} where $V_{GS} > V_{miller}$. Once C_{DS} if fully discharged and V_{miller} is reached, C_{GD} begins to discharge. During this phase $V_{miller} > V_{GS} > V_{th}$. Finally, once $V_{GS} < V_{th}$, C_{GS} discharges and the off-state drive voltage is achieved.

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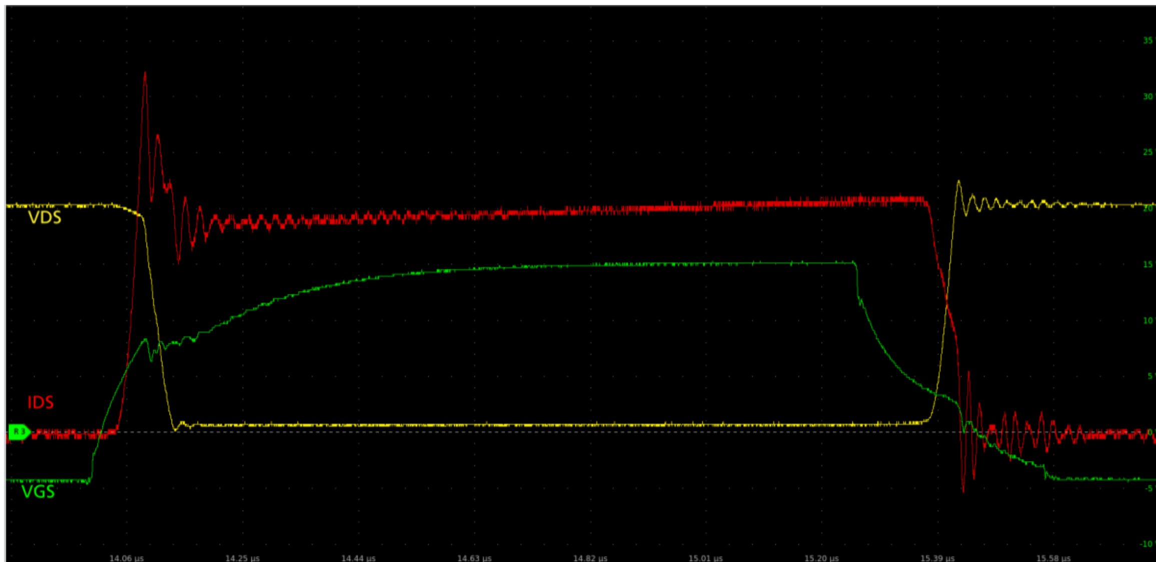

Figure 1: Turn-on and Turn-off transient with V_{GS}, V_{DS} and I_{DS}

Wolfspeed Devices

The typical V_{th} of Wolfspeed devices is 2.5 V at room temperature. Wolfspeed recommends utilizing the recommended operational and max ranges provided in the datasheet of the specific device.

3. Impact of V_{GS} on Static Characteristics

V_{GS} influences many static values provided in the datasheet with the most important being the device's $R_{DS(on)}$ value. The applied gate voltage impacts the current carrying capability of the SiC MOSFET, and Wolfspeed datasheets capture the value at the recommended turn-on gate voltage. For 3rd generation devices and onwards, the standard recommended turn-on gate voltage is $V_{GS(on)}$ = +15 V. For 2nd generation devices $V_{GS(on)}$ = +18 V. Not stated in datasheets is the change of $R_{DS(on)}$ when moving to lower or higher turn-on gate voltages such as +11 V or +19 V. Instead, IV curves are provided to display a series of various parameters. The curves taken in the following section were captured on a Keysight® B1506A standard curve tracer. The devices under test (DUTs) are the Gen 3 and the Gen 4 dies in TO247-4L packages. Both selected dies are rated for 1200 V and part of the Wolfspeed's automotive grade SiC MOSFETs.

3.1 Impact of V_{GS} on Current Capability

The typical IV curves for Wolfspeed's Gen 3 device as a function of gate voltage V_{GS} for 25°C and 175°C are shown in Figure 2. The gate voltage incrementally increases in steps of 1 V from +10 V to +19 V at 25°C and 175°C.

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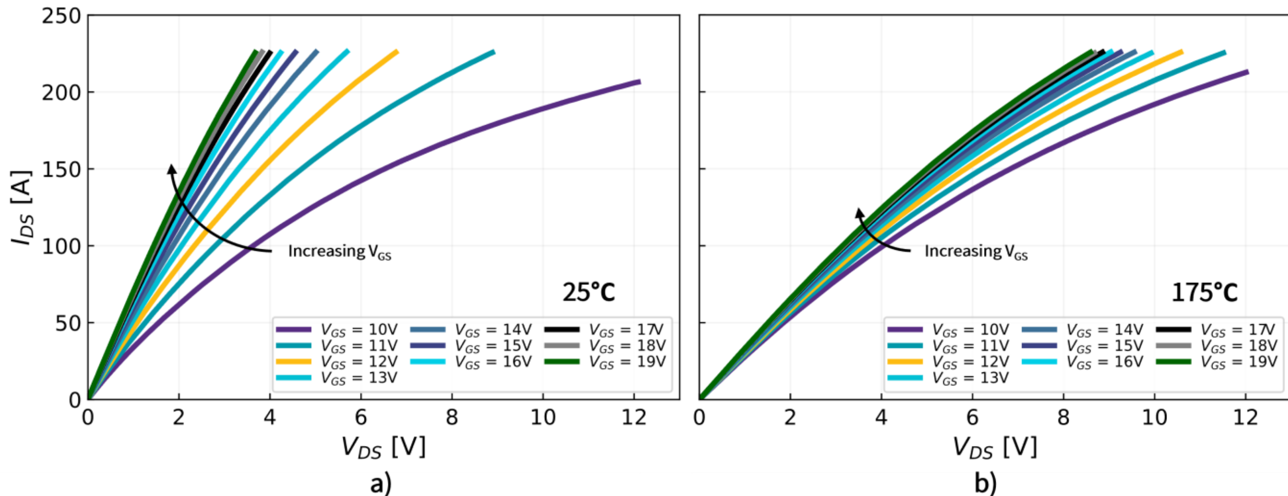

Figure 2: I_{DS} vs. V_{DS} with various V_{GS} applied to the Gen 3 device at (a) 25°C and (b) 175°C

Starting at 10 V of gate-source voltage, the current is limited by the inversion channel. Increasing the V_{GS} to the recommended gate voltage of 15 V increases the current carrying capability quite significantly. Above V_{GS} = +15 V, the change in current becomes limited due to the saturation of the channel.

Similar tests were done on the Gen 4 device, with the gate voltage incrementally increased in steps of 2 V from +11 V to +19 V at 25°C and 175°C (Figure 3).

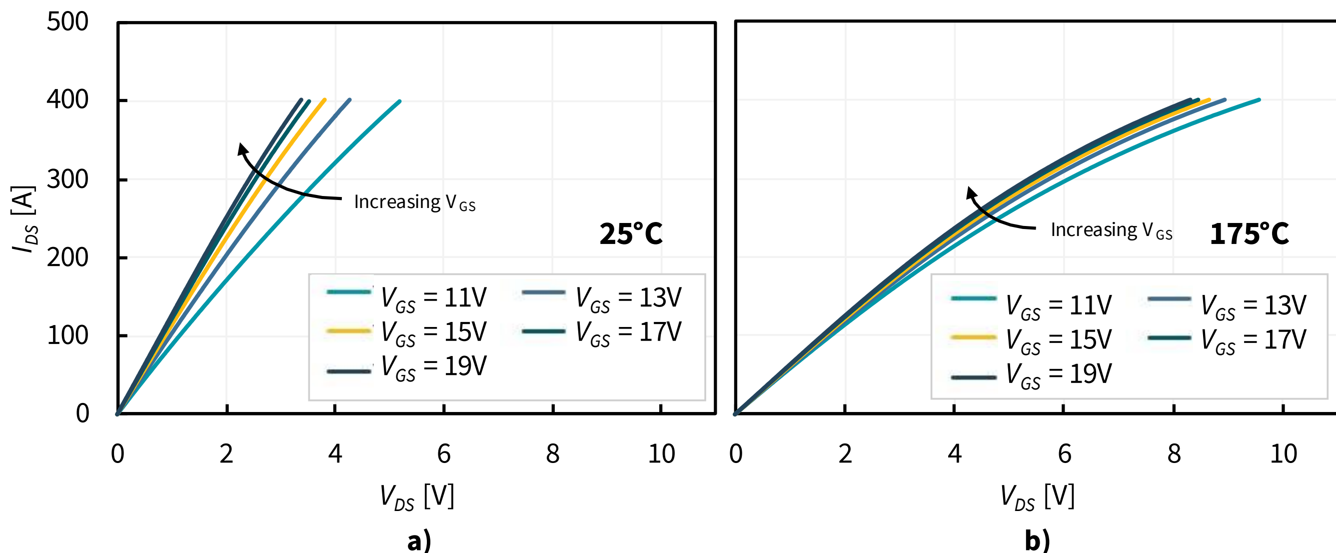

Figure 3: I_{DS} vs. V_{DS} with various V_{GS} applied to the Gen 4 device at (a) 25°C and (b) 175°C

3.2 Impact of V_{GS} on $R_{DS(on)}$

Applying Ohm's Law to the IV curves, similar plots can be constructed for $R_{DS(on)}$. Figure 4 shows the impact of V_{GS} on $R_{DS(on)}$ at 25°C and 175°C for Gen 3 device. Figure 5 shows the impact of V_{GS} on $R_{DS(on)}$ at 25°C and 175°C for Gen 4 device.

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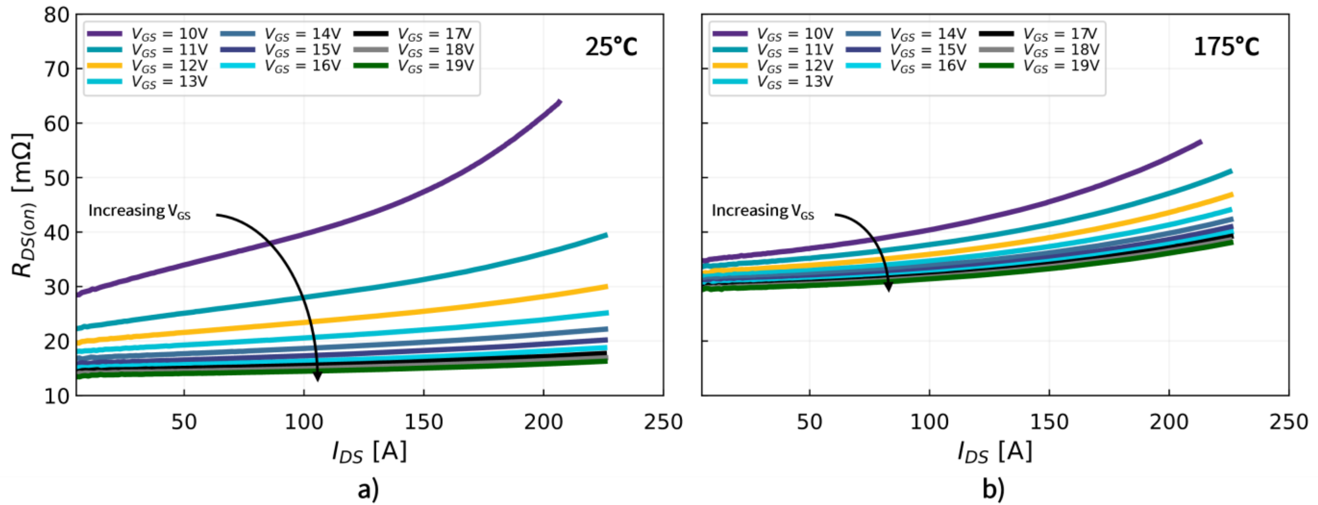

Figure 4: $R_{Ds(on)}$ vs. I_{DS} at various V_{GS} conditions for Gen 3 device at a) 25°C and b) 175°C

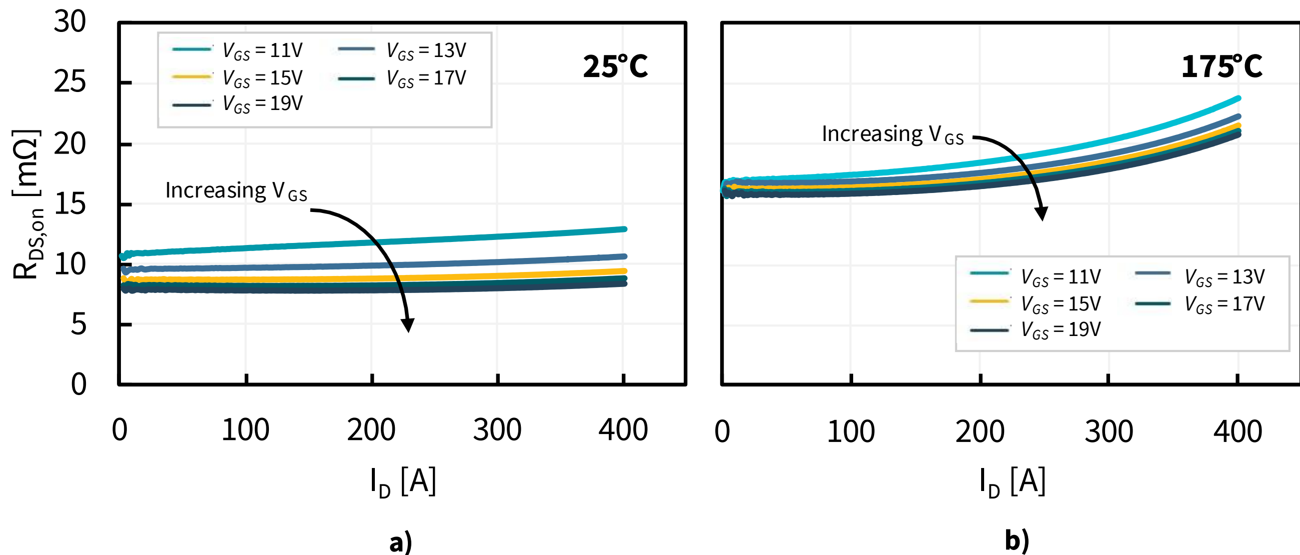

Figure 5: $R_{Ds(on)}$ vs. I_{DS} at various V_{GS} conditions for Gen 4 device at a) 25°C and b) 175°C

$R_{DS(on)}$ is reduced significantly as V_{GS} increases from +10 V to +15 V. As the channel saturates above +15 V, the reduction in $R_{DS(on)}$ becomes limited.

Table 1 focuses on the $R_{DS(on)}$ for the Gen 3 device at the rated current at 25°C and 175°C while Table 2 focuses on the $R_{DS(on)}$ for the Gen 4 device at the rated current at 25°C and 175°C at various V_{GS} levels.

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V_{GS} [V]	$R_{DS(on)}$ [mΩ] @ 25°C / 175°C
10	36.3 / 38.3
11	26.4 / 36.2
12	22.4 / 34.7
13	19.8 / 33.6
14	18.1 / 32.8
15	16.9 / 32.2
16	15.9 / 31.7
17	15.2 / 31.3
18	14.6 / 31.0
19	14.2 / 30.6

Table 1: Static values of $R_{DS(on)}$ at the rated current, for the Gen 3 device for various V_{GS}

V_{GS} [V]	$R_{DS(on)}$ [mΩ] @ 25°C / 175°C
11	11.4 / 17.5
13	9.65 / 16.6
15	8.73 / 16.1
17	8.19 / 15.8
19	7.84 / 15.6

Table 2: Static values of $R_{DS(on)}$ at the rated current, for the Gen 4 device for various V_{GS}

3.3 Turn on/off Waveforms

One of the consequences of varying the V_{GS} is its impact on the turn-on and turn-off waveforms of the device. Using a Keysight® B1506A, the impact of V_{GS} on the V_{DS} turn-on and turn-off waveforms are shown in Figure 6, Figure 7. The current (I_{DS}) was limited to the rated current and the device was tested at various V_{GS} values at both 25°C and 175°C.

Figure 6 shows how V_{GS} and $R_{DS(on)}$ affect the V switching transients for the Gen 3 device and similarly, Figure 7 shows how V_{GS} and $R_{DS(on)}$ affect the V switching transients for the Gen 4 device. The change in voltage over time, dV_{DS}/dt, during turn on and off increases as V_{GS} increases and $R_{DS(on)}$ decreases. $R_{DS(on)}$ also decreases with temperature, hence having V_{DS} switch faster at 175°C.

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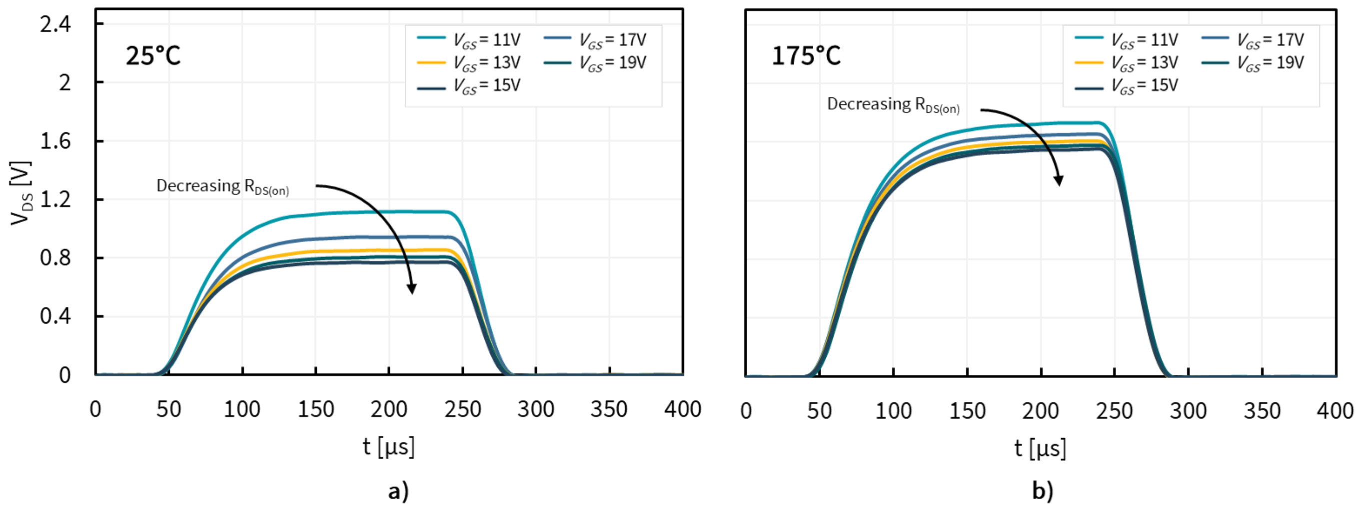

Figure 6: V_{DS} vs time for various V_{GS} for the Gen 3 device at a) 25°C and b) 175°C

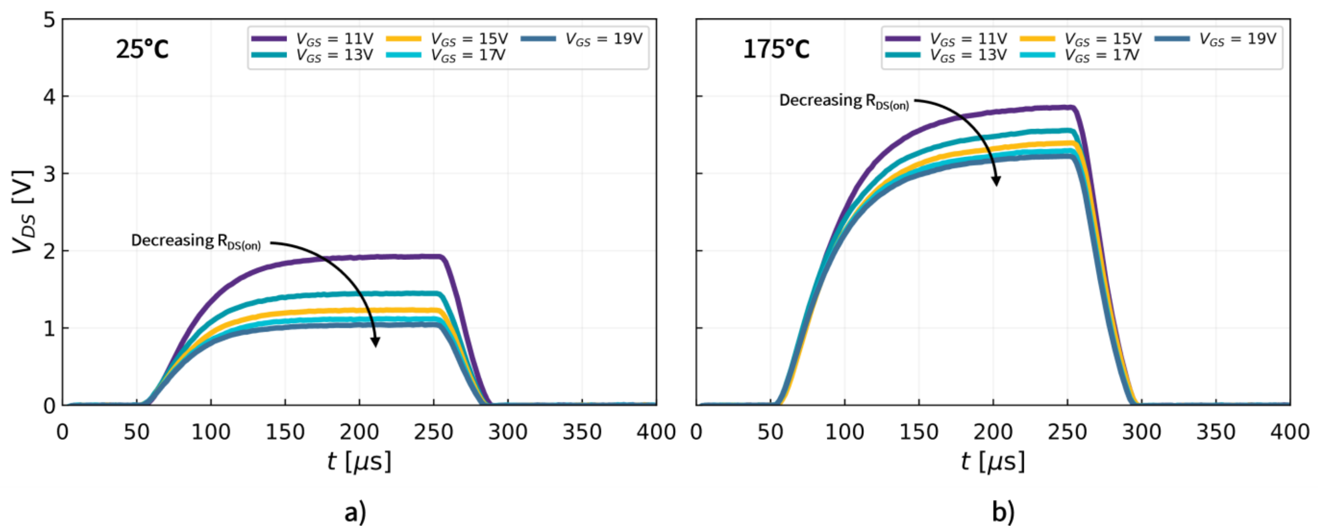

Figure 7: V_{DS} vs time for various V_{GS} for the Gen 4 device at a) 25°C and b) 175°C

4. Impact of V_{GS} on Dynamic Characteristics

V_{GS} will also impact dynamic measurements such as switching times and switching losses. Dynamic test measurements were performed using a clamped inductive load (CIL) PCB designed to have low parasitic inductance and a test rack consisting of a BK Precision® 9130 low-voltage power supply, a Keysight® 33210A function generator, an Acopian® high-voltage power supply, and a Tektronix® MSO58B oscilloscope. A TIVP IsoVu optically-isolated low-voltage probe was used for measuring V_{GS}, a THDP02000 high-voltage differential probe was used for V_{DS}, and a current viewing resistor (CVR) from T&M Research Products® was used to measure I_{DS}.

4.1 Switching Losses

To check the impact of V_{GS} on switching losses, CIL tests were performed at different turn-on gate voltages shown in Figure 8 and Figure 9. The devices were switched at a constant turn-off voltage of -4 V.

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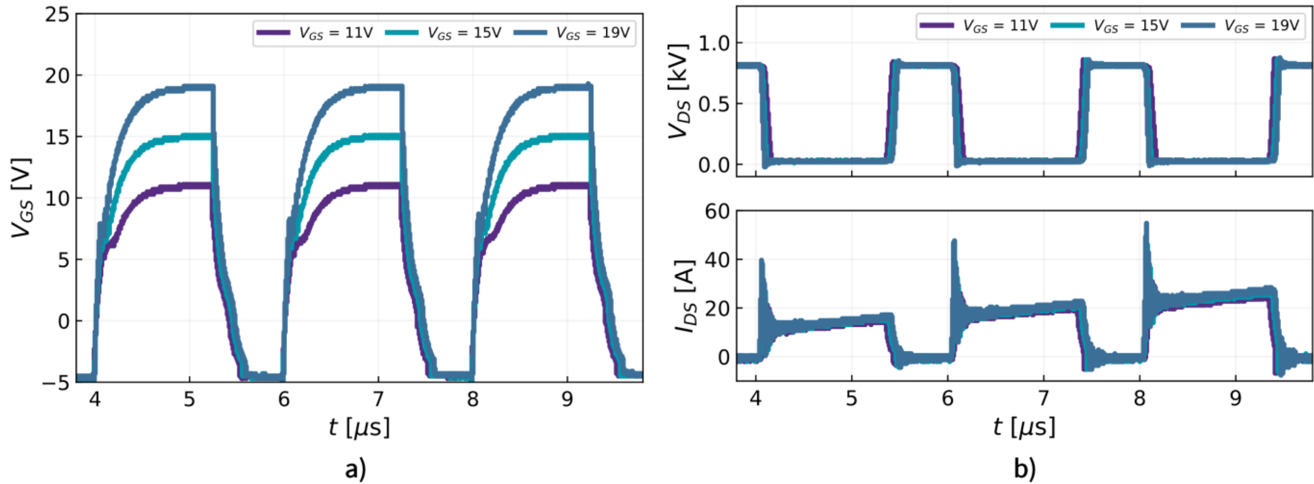

Figure 8: Transient V_{GS}, V_{DS} and I_{DS} waveforms for the Gen 3 device; V_{DS} = 800 V; Temp. = 25°C

Figure 8 shows three pulses from the CIL test. The first noticeable difference between the different $V_{GS(on)}$ waveforms is that the test current slightly increases. This is caused by the difference in freewheeling time while the DUT is held off.

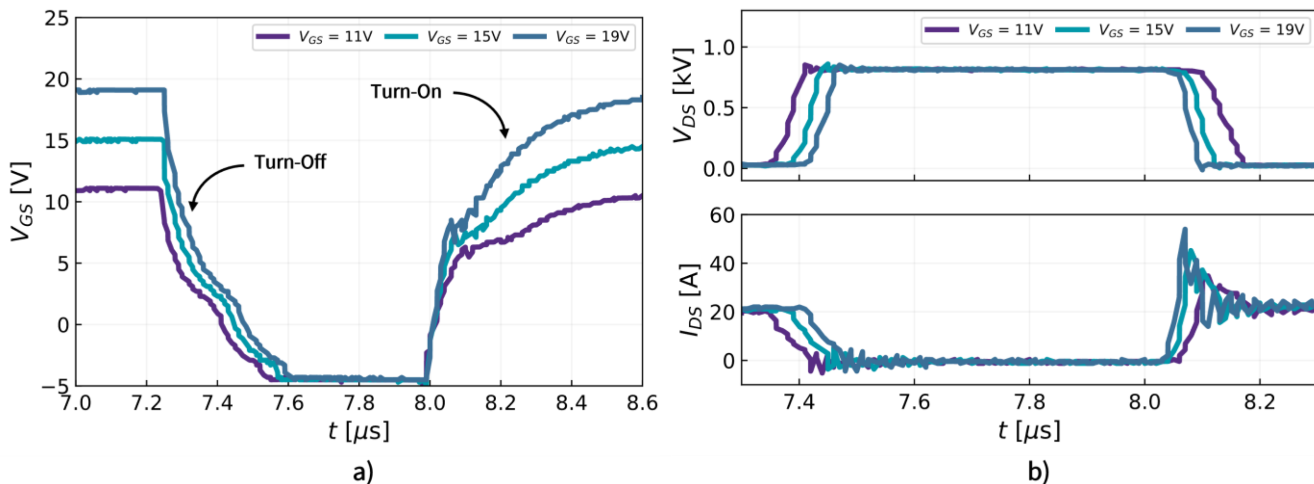

Figure 9: Zoom-in of V_{GS}, V_{DS} and I_{DS} vs. time for the Gen 3 device

Figure 9 zooms in to show one turn-on event and one turn-off event. At both switching events there is a time delay related to V_{GS}. During this delay no work is carried out by the system and energy is lost. This energy is also known as switching loss energy, E_{sw}. Equations (1) and (2) describe the turn-on and turn-off time delays as they relate to the $V_{GS(on)}$ and $V_{GS(off)}$ [3]. R_G and C_{iss} are constant for all measurements.

$$t_{d(on)} = R_g C_{iss} \ln\left(\frac{V_{gs(on)} - V_{gs(off)}}{V_{gs(on)} - V_{th}}\right) \quad (1)$$

Thus, the turn-on delay relies on the delta between $V_{GS(on)}$ and V_{th}, and so as V_{GS} increases the delay decreases.

$$t_{d(off)} = R_g C_{iss} \ln\left(\frac{V_{gs(on)} - V_{gs(off)}}{V_{miller} - V_{gs(off)}}\right) \quad (2)$$

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Equation (2 describes the time delay during turn-off where the delay is dependent on the delta between $V_{GS(on)}$ and $V_{GS(off)}$. Thus, the resulting trend is that for increasing $V_{GS(on)}$, $t_{d(off)}$ will increase. The delays measured here are plotted in Figure 10(a), Figure 11(a).

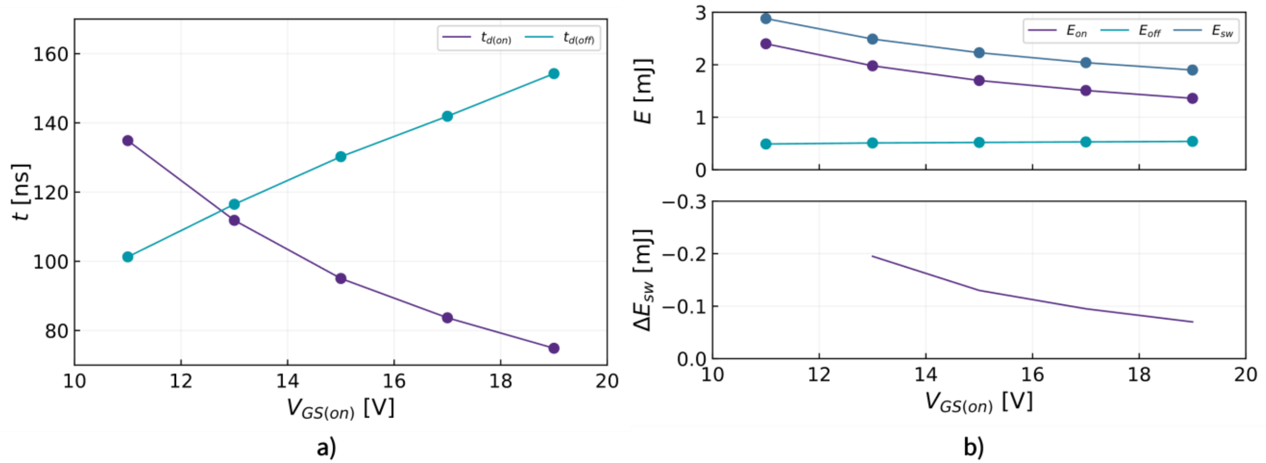

Figure 10: a) Turn-On and Turn-Off time delay vs. $V_{GS(on)}$ b) Switching Energy vs. $V_{GS(on)}$ & �E_{sw} vs. $V_{GS(on)}$ for the Gen 3 device

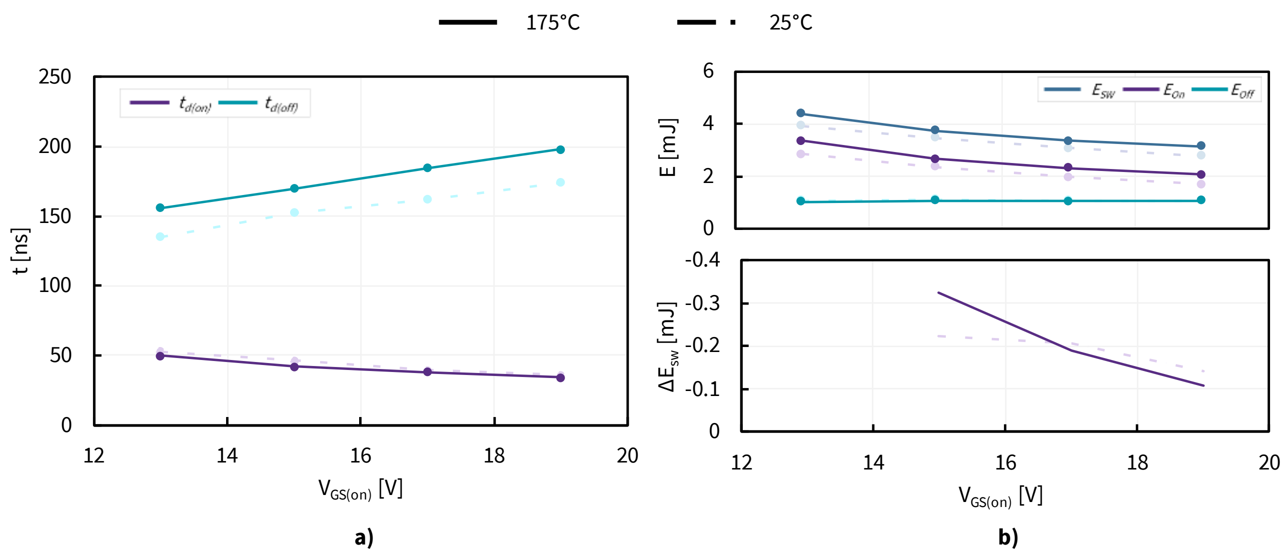

Figure 11: a) Turn-On and Turn-Off time delay vs. $V_{GS(on)}$ b) Switching Energy vs. $V_{GS(on)}$ & ΔE_{sw} vs. $V_{GS(on)}$ for the Gen 4 device at 25°C and 175°C

Figure 10(b) & Figure 11(b) shows the on (E_{on}), off (E_{off}), total switching energy (E_{sw}), and change in total switching energy (ΔE_{sw}) as functions of turn-on voltage. Although the total switching energy decreases as $V_{GS(on)}$ increases, the benefits in energy saved abate at higher turn-on values. When the turn-on voltage for the Gen 3 device increased from 11 V to 13 V, the total switching energy decreased by ~200 J/V, a 16% improvement while from 17 V to 19 V it reduced by ~75 J/V, a 7% improvement. The total reduction in total switching energy over the $V_{GS(on)}$ values measured here improved from ~2.5 mJ at 11 V to ~1.5 mJ at 19 V, a 67% reduction.

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5. Influence of V_{GS} on Short-Circuit Capability

The short-circuit capability of the device will also vary with $V_{GS(on)}$. During a short-circuit event, the device dissipates a large amount of energy in a short period of time, spiking in the device's junction temperature and causing failure. The current transient (di/dt) at turn-on has a direct relationship to short-circuit withstand time, t_{SC}, and short-circuit withstand energy (E_{SC}) [4]. To demonstrate this relationship, short-circuit tests were performed on a Gen 3 device following the standard test-to-failure (TTF) method and IEC and JEDEC standards [5] [6]. Short-circuit tests were performed using an Acopian® high-voltage power supply, a BK Precision® 9130 low-voltage power supply, an Agilent® 33250A 80 MHz function generator and a Tektronix® DPO 5034B digital phosphor oscilloscope. A Tektronix® Rogowski current probe was used to measure I_{DS}, a Tektronix® TPP1000 passive probe was used to measure V_{GS}, and Tektronix® TPP0850 probe for V_{DS}.

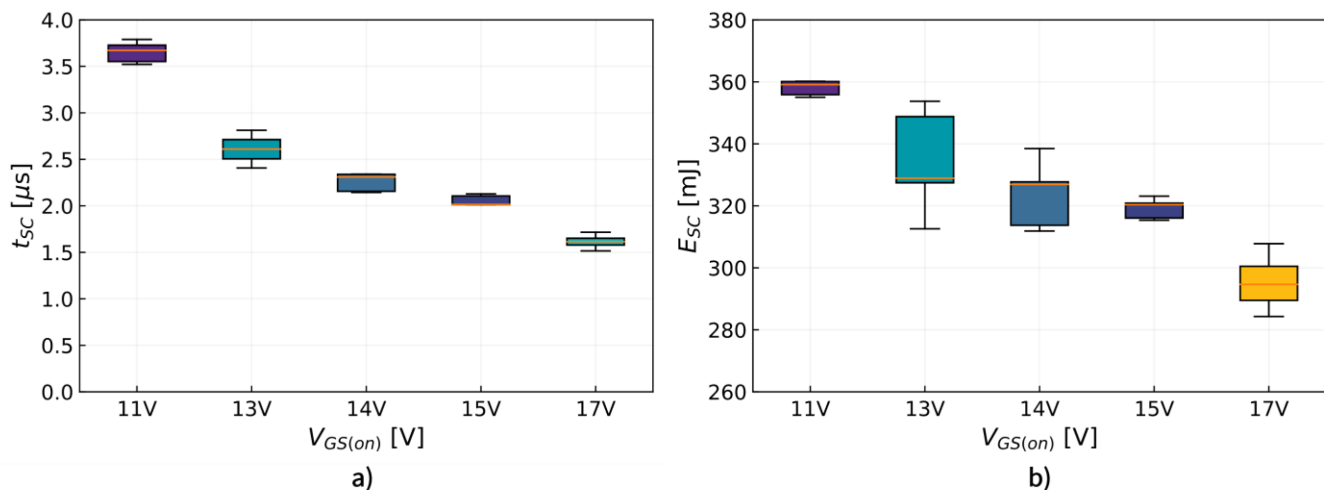

Figure 12: a) t_{sc} vs. V_{GS} and b) E_{sc} vs. V_{GS} for the Gen 3 device at 25°C

In Figure 12, short-circuit time and energy both decrease with increasing gate voltage and impact device performance significantly. Lowering the turn-on gate voltage can increase short-circuit withstand time and energy. The higher $R_{DS(on)}$ value seen at lower $V_{GS(on)}$ values limits the turn-on and peak short-circuit current. When these currents are managed, the critical failure temperature of the device takes longer to reach. A 2 µs minimum short-circuit time increase is gained by decreasing the $V_{GS(on)}$ from 17 V to 11 V.

6. Conclusion

Ultimately, V_{GS} plays a critical role in the performance of a SiC MOSFET. When designing a power system, the operational V_{GS} must be considered, and trade-offs may occur. Increasing V_{GS} will allow for lower $R_{DS(on)}$ and faster switching times, leading to lower conduction and switching losses and thus improving system efficiency. With the Gen 3 device, increasing the gate voltage can be advantageous in low $R_{DS(on)}$ applications, showing a 19% reduction in $R_{DS(on)}$ between +15 V and +19 V at 25°C. With the Gen 4 device, a 11% reduction in $R_{DS(on)}$ is seen between +15 V and +19 V at 25°C. The benefits gained from increasing V_{GS} quickly diminish for values above +15 V and at higher temperatures. Alternatively, for applications that require robust parts, short-circuit performance can be improved when moving to lower V_{GS} operating conditions. Thus, any change in V_{GS} needs to be tested and validated to understand the device characteristics under the new conditions. Lastly, performing tests with

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V_{GS} values outside of the operational and maximum ranges provided in the device's datasheet will alter the lifetime of the device and possibly degrade the immediate performance of the device.

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Revision History

Date	Revision	Changes	Author
November 2024	1	Initial Release	Nicolas Lozada; Sharan Sharma
August 2025	2	Update with Gen 4	Sharan Sharma

References

[1] M. Bhatnagar and B. J. Baliga, "Comparison of 6H-SiC, 3C-SiC, and Si for Power Devices," *IEEE Transtionction on Electronic Devices,* vol. 40, no. 3, pp. 645-655, 1993.

[2] B. J. Baglia, Fundamentals of Semiconductor Devices, 2 ed., Raleigh: Springer, 2019, p. 292.

[3] X. Wang, Z. Zhao, K. Li, Y. Zhu and K. Chen, "Analytical Methodology for Loss Calculation of SiC MOSFETs," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 7, no. 1, pp. 71-83, 2019.

[4] Wolfspeed; Nicolas Lozada; Felix Fraas, "SiC MOSFET Short Circuit Application Note," Wolfspeed, Durham, 2023.

[5] JEDEC, "Short Circuit Withstand Time Test Method," JEDEC Solid State Technology Association, Arlington, 2002.

[6] IEC, "Discrete Semiconductor Devices - Metal-oxide-semiconductor field-effect transistors (MOSFETs) for power switching applications," International Electrotechnical Commission, Geneva, 2004.

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