Whitepaper

How to interpret SiC MOSFET datasheet parameters

Apply them in a typical power electronics circuit design

By Dr. Sebastian Fahlbusch, Manager – Power Product Application Competence Center

By Zhe Yu, Senior Power Application Engineer

Silicon Carbide (SiC) MOSFETs bring many advantages to high power electronics applications like charging stations, uninterruptible power supplies (UPS), solar photovoltaic (PV), motor drives, and battery energy storage systems (BESS). Furthermore, they can be used in various electric vehicle (EV) applications including on-board chargers (OBC), DC-DC converters, inverters and HVAC systems.

The broad range of use-cases can make it difficult for engineers to interpret which datasheet parameters have the most impact on power losses, system efficiency and device junction temperature in their designs. This understanding is required so they can compare and contrast the performance of devices from different manufacturers in order to determine which is best for their application. Nexperia recently introduced its first 1200 V silicon carbide (SiC) MOSFETs - including the NSF040120L4A0 - and in this whitepaper, it explores essential datasheet parameters for this device type. Additionally, to demonstrate the class-leading features of this SiC MOSFET, this paper then describes a methodology for using these essential datasheet parameters to estimate device performance in a widely-used bidirectional DC-DC-converter topology.

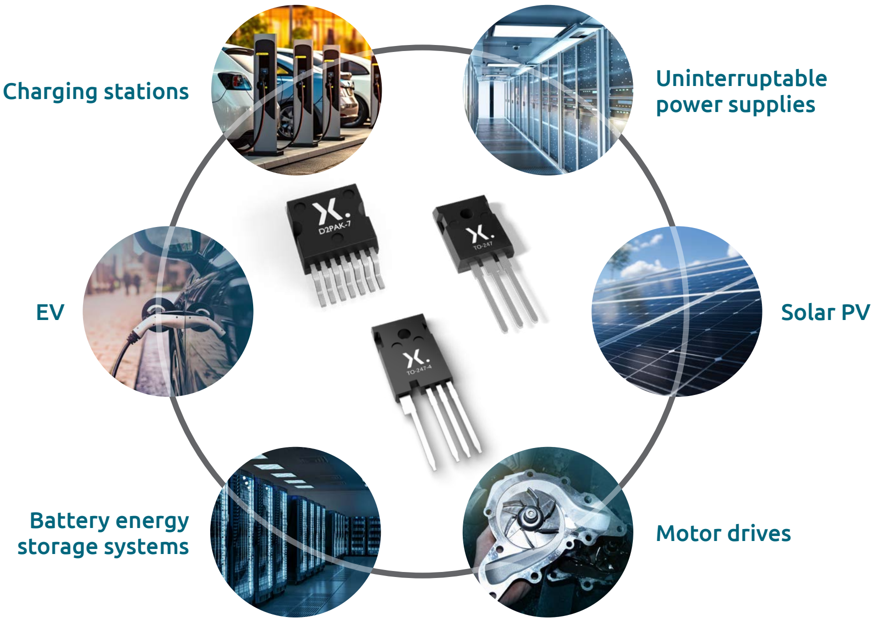


Figure 1: SiC MOSFETs can be employed in a diverse range of applications

While there are many potential applications for SiC MOSFETs, these devices are typically employed in a small number of sub-circuit topologies like the boost converter, the three-phase inverter and the galvanically isolated DC-DC converter. A common feature of these topologies is that they each feature a basic cell structure comprising either an inductor, a switching transistor and diode, or else an inductor and two switching transistors as shown in the following figure. This allows the behavior of more complex to be deduced, because they obey the same principles. Hence, for all topologies the same relevant datasheet parameters apply and can be used to determine device performance in an application. It is important to note, however, that individual applications place different weightings on each parameter as discussed in the following sections.

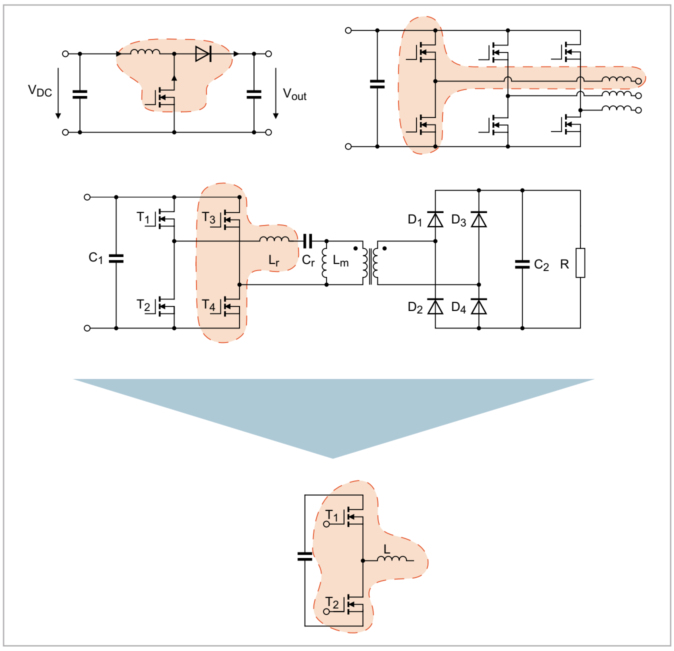


Figure 2: The boost converter, the three-phase inverter and the galvanically isolated DC-DC converter all feature a common basic cell

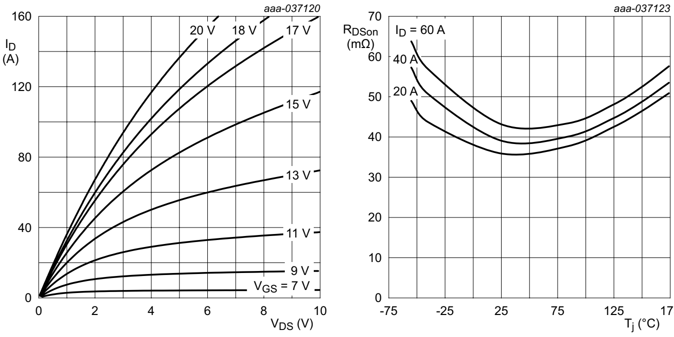
Table 1 summarizes the essential datasheet parameters for determining device performance. These include on-resistance ($R_{DS(on)}$), total gate charge (Q_G), gate-charge ratio ($Q_{GD/QGS}$), threshold voltage (V_{GSth}), switching energies (E_{on} and E_{off}) as well as thermal resistance (R^{th}) and thermal impedance (Z_{th}).

Parameter	Has impact on	Influenced by
$R_{DS(on)}$	Conduction loss	T_j, V_{GSon}, i_D
Q_G	Drive loss, delay times	V_{GSon}, V_{GSoff}, i_D
Q_{GD}/ Q_{Gs}	Switching stability	i_D, V_{DS}
V_{GSth}	Delay time, safety margin V_{GSoff}	T_j, V_{DS} (implicitly)
E_{on} & E_{off}	Switching loss	T_j, V_{GSon}, V_{GSoff}, R_G, V_{DC}, i_{Load}
$R_{th(j-c)}$ & $Z_{th(j-c)}$	T_j	

Table 1: Critical SiC MOSFET device parameters for power electronics applications

Conduction performance

The value of $R_{DS(on)}$ impacts the conduction losses in a SiC MOSFET during its on-state and is influenced by several factors. $R_{DS(on)}$ describes the residual on-resistance of a static device that is fully turned on and Nexperia describes this parameter under 'output characteristics' in the datasheet for the NSF040120L4A0, as shown in the following figure. $R_{DS(on)}$ is the gradient (slope) of the current-voltage (IV) curve at the operating current for an application, with steeper curves indicating lower on-resistance. $R_{DS(on)}$ is not a constant parameter because it changes in response to variations in gate-source voltage (V_{GS}), drain current (I_D) and temperature. $R_{DS(on)}$ has a distinct positive temperature coefficient characteristic meaning its value is higher at elevated temperatures. The datasheet graphs shown in Figure 3 provide all of the information a designer requires to calculate the gradient of the IV curve and extract the value of $R_{DS(on)}$ at the operating point of their application.

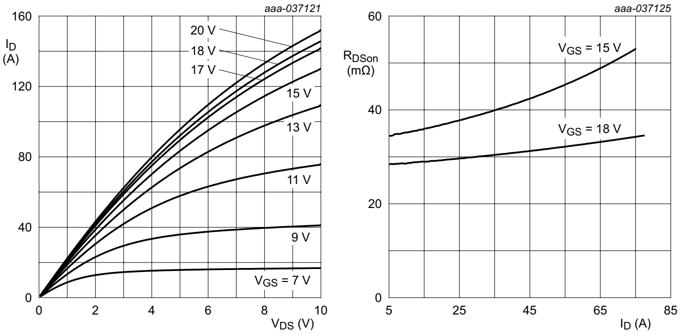


T_j = 25 °C; t_p = 100µs

V_{GS} = 15 V; t_p = 100µs

Fig 1. Output characteristics: drain current as a function of drain-source voltage; typical values

Fig 4. Drain-source on-state resistance as a function of junction temperature; typical values



T_j = 175 °C; t_p = 100µs

T_j = 25 °C; t_p = 100µs

Fig 2. Output characteristics: drain current as a function of drain-source voltage; typical values

Fig 6. Drain-source on-state resistance as a function of drain current; typical values

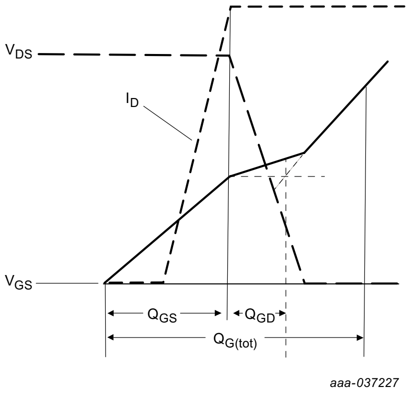
Figure 3 Datasheet Figs. 1, 2, 4 and 6 in Nexperia's SiC MOSFET datasheet describe influences on $R_{DS(on)}$

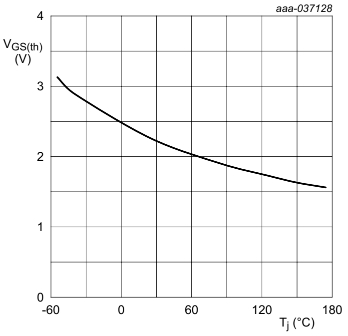
Switching performance

Besides $R_{DS(on)}$ the dynamic switching performance of MOSFETs is crucial to achieve maximum performance in switching applications. Threshold voltage V_{GSth}, gate charge Q_G, gate charge ratio Q_{GD}/Q_{GS} and switching energies E_{on} & E_{off} are relevant parameters specified in the datasheet.

Switching procedure, threshold voltage and gate charge

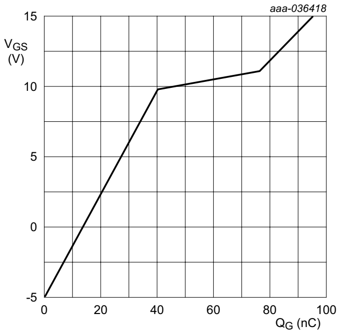
Figure 4 shows a simplified illustration of the turn-on process for a SiC MOSFET. The device is initially in the off state ($V_{GS} < V_{GSth}$) and therefore fully blocks the applied drain-source voltage (V_{DS}) with virtually no current flowing (except for a negligible amount of leakage current).





I_D = 4 mA

Fig 9. Gate-source treshold voltage as a function of junction temperature; typical values



V_{DD} = 800 V; I_D = 40 A; T_j = 25 °C

Fig 12. Gate-source voltage as a function of gate charge; typical values

Dynamic characteristics				
$Q_{G(tot)}$	Total gate charge	V_{DD} = 800 V; I_D = 40 A; V_{GS} = -5/+ 15 V; T_j = 25 °C	95	nC
Q_{GS}	gate-source charge		40	nC
Q_{GD}	gate-drain charge		30	nC

Figure 4 Datasheet Figs. 9 and 12 show the effect of gate charge and temperature on threshold voltage

Switching performance

As the gate voltage rises, predominantly the gate-source capacitor (C_{GS}) begins to charge until V_{GS} reaches the threshold voltage V_{GSth}, initiating current commutation that results in a significant increase in the drain current. As current flow increases, the gate-source voltage continues to rise while the full blocking voltage is still present across the drain-source terminals of the device, until current commutation is complete. Then the device conducts the full current and the gate voltage reaches a value called the 'plateau'. At this point, C_{GS} is almost fully charged and the gate-drain C_{GD} capacitance begins to discharge leading to the simultaneous decrease of the drain-source voltage V_{DS}. Note that for simplicity, reverse recovery and capacitive charging effects are neglected. Unlike in silicon power transistors, where the V_{GS} plateau is almost flat, SiC MOSFETs gate plateau shows a distinct V_{GS} ramp during voltage commutation.

The SiC MOSFET's short-channel effect, causes a V_{DS} dependent threshold voltage meaning the voltage across the gate-source capacitor must continue to be charged (albeit only by a small amount) to compensate. Despite this, while drain-source discharging is taking place, most of the gate charge is still being delivered to Q_{GD}. After voltage commutation, the gate is further charged in order to reach the target value of $R_{DS(on)}$ as shown previously. The total amount of charge which must be delivered by the gate driver is:

$$Q_{G(tot)} > Q_{GS} + Q_{GD}$$

and therefore higher than the simple sum of $\mathbf{Q_{GS}}$ and $\mathbf{Q_{GD}}$.

These parameters are application-dependent, including the on- and off-state voltage levels, the operating current, the drain-source voltage and also the threshold voltage (which is affected by the junction temperature). The gate charge components can be extracted from datasheet Fig. 12 and the table of dynamic characteristics. Datasheet Fig. 9 shows how the threshold voltage of a SiC MOSFET gradually declines as junction temperature rises. This information is included in the datasheet to provide additional information for designers to ensure safe operation under all application conditions.

Switching energies - Eon and Eoff

During turn-on and turn-off switching transitions, the simultaneous occurrence of drain-source current and the drain-source voltage results in the so-called switching energy losses E_{on} and E_{off}. Usually, both switching energy losses are determined by measuring V_{DS} and I_D and by subsequent integration of the instantaneous power (product of V_{DS} and I_D) as shown in Figure 5.

$$E_{ON} = \int_{t_{L1}}^{t_{U1}} p(t)\mathrm{d}t = \int_{t_{L1}}^{t_{U1}} V_{DS}(t) \cdot I_D(t)\,\mathrm{d}t$$

$$E_{OFF} = \int_{t_{L2}}^{t_{U2}} p(t)\mathrm{d}t = \int_{t_{L2}}^{t_{U2}} V_{DS}(t) \cdot I_D(t)\,\mathrm{d}t$$

The integral limits are defined as 10% of the current and 10% of V_{DS} for lower and upper limit for E_{on} and vice versa for E_{off} (represented by the shaded area in the figure below).

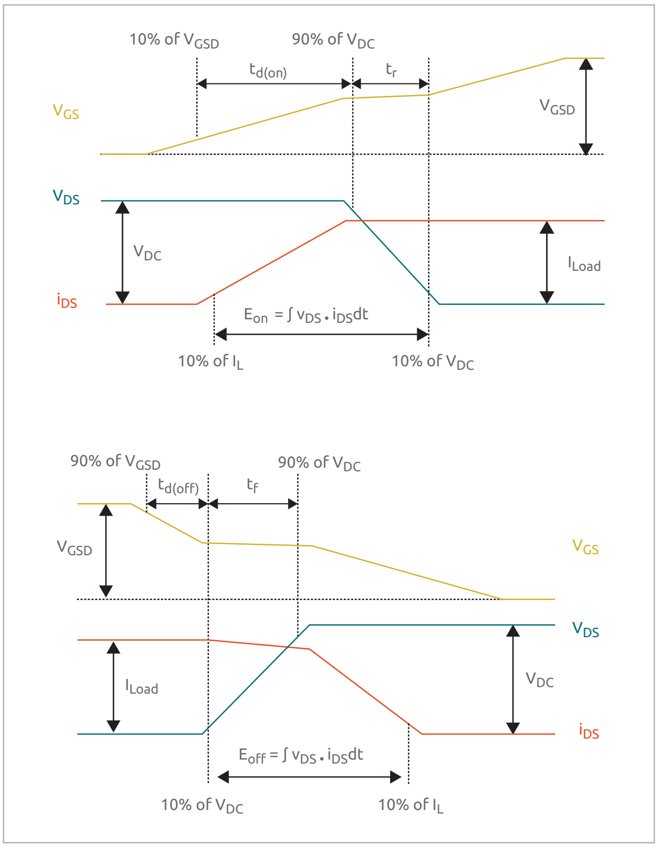
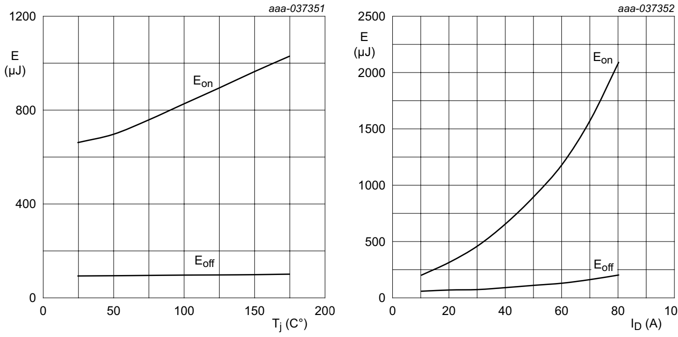


Figure 5 Definition of switching losses and switching times

Switching energies (E_{on} and E_{off}) are measured by Nexperia in the laboratory and are illustrated in datasheet Fig. 13 as a function of junction temperature. These energies are also represented as a function of the drain current in datasheet Fig.14 . Switching losses and their duration, as a function of external gate resistance are shown in datasheet Fig. 15 and Fig. 16 respectively.

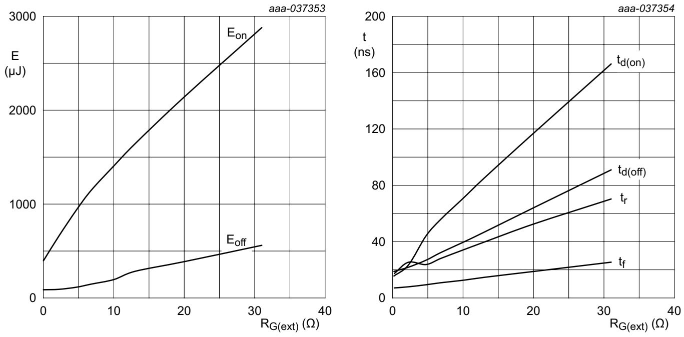


V_{DD} = 800 V; I_D = 40 A; V_{GS} = -5/+ 15 V; $R_{G(est)}$ = 2.2 Ω; L_L = 82 µH

V_{DD} = 800 V; V_{GS} = -5/+ 15 V; $R_{G(est)}$ = 2.2 Ω; L_L = 82 µH; T_j = 25 °C

Fig 13. Switching loss as a function of junction temperature; typical values

Fig 14. Switching loss as a function of drain current; typical values



V_{DD} = 800 V; I_D = 40 A; V_{GS} = -5/+ 15 V; L_L = 82 µH; T_j = 25 °C

V_{DD} = 800 V; I_D = 40 A; V_{GS} = -5/+ 15 V; L_L = 82 µH; T_j = 25 °C

Fig 15. Switching loss as a function of $R_{G(ext)}$; typical values

Fig 16. Switching times as a function of $R_{G(ext)}$; typical values

Figure 6 Datasheet Figs. 13, 14, 15 and 16 show information about switching energies

Gate charge ratio (Q_{GD}/Q_{GS})

The gate charge ratio is a crucial indicator of the degree to which a device is protected against self turn-on (also called Miller turn-on) as illustrated in Figure 7. During freewheeling operation of the body diode in one SiC MOSFET, and turn-on of the opposite SiC MOSFET, C_{GD} and C_{DS} of the freewheeling device are charged. This process can lead to safety concerns associated with unwanted self turn-on, a situation that can arise if the charge stored in the gate-drain capacitance (Q_{GD}) exceeds that stored in the gate-source capacitance (Q_{GS}), in combination with the impedance path to the gate driver being too high. To avoid the need to include additional safety measures (protecting against this phenomenon) designers should select a SiC MOSFET in which:

$$Q_{GD)} < Q_{GS}$$

Nexperia's NSF040120L4A0 is fabricated to ensure that $Q_{GD} < Q_{GS}$ by design and therefore it does not require additional safety measures to protect against self-turn on.

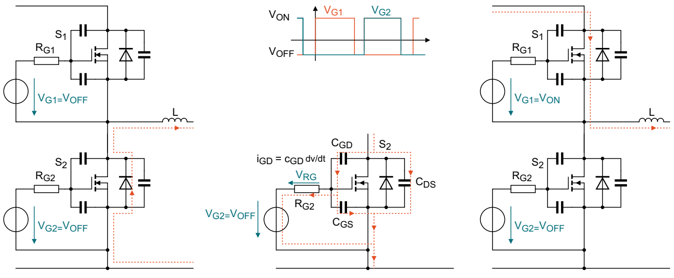


Figure 7 Illustration of Miller turn-on phenomenon

Thermal resistance - $R_{th(j-c)}$ and thermal impedance $Z_{th(j-c)}$

Besides conduction and thermal performance, thermal performance is another crucial device metric and is expressed by thermal impedance $Z_{th(j-c)}$ and steady-state thermal resistance $R_{th(j-c)}$ to quantify operating losses. Both are needed to determine device junction temperature during normal operation and can be extracted using datasheet Fig. 20 which shows the transient thermal impedance. In most power electronics applications, a switching device cycles between an on and off state according to the applied duty cycle and this causes the device to periodically heat up and cool down. This results in an 'average' device operating temperature that depends on the thermal resistance, $R_{th(j-c)}$ (the thermal resistance from device junction-to-case which is shown under thermal characteristics in the datasheet) and the pulse duration (dashed line in Figure 8). However, due to the nature of switching operation, the actual instantaneous junction temperature cycles around this average value and the magnitude of the ripple depend on the duty cycle as well as the pulse frequency which both influence the transient thermal impedance $Z_{th(j-c)}$. By analyzing the thermal performance, designers can determine operating temperature boundaries and the effect that these temperatures could have over the lifetime of a device.

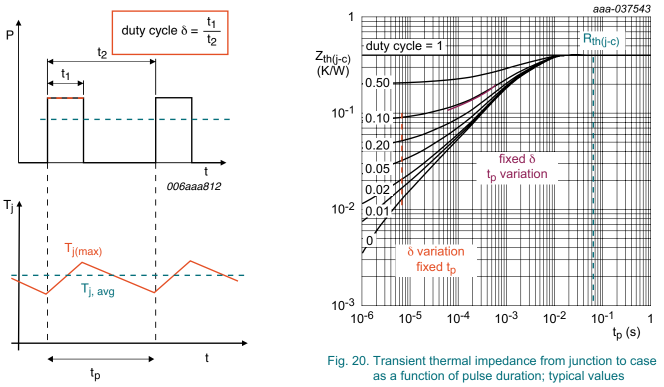


Fig. 20. Transient thermal impedance from junction to case as a function of pulse duration; typical values

Thermal characteristics

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
$R_{th(j-c)}$	Thermal resistance from junction to case		-	0.68	0.82	K/W

Figure 8 Datasheet Fig. 20 shows device thermal characteristics

Using datasheet parameters for design-in decisions in applications

Before making a design-in decision for a SiC MOSFET for an application, it is important to estimate the power losses in the device and its junction temperature during operation. However, the estimation is not straightforward due to the mutual interaction between electrical properties and junction temperature.

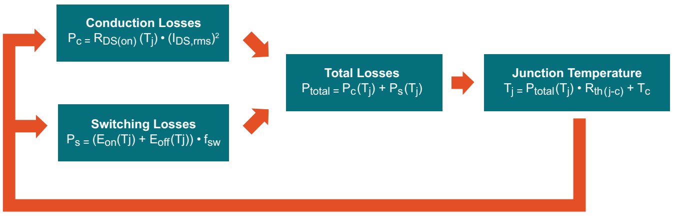


Figure 9 Iterative calculation flow for estimating power losses and junction temperature

As shown in Figure 9, the conduction and switching losses are dependent on the junction temperature. Simultaneously, the junction temperature is affected by the total losses in the SiC MOSFET. The power losses and junction temperature must therefore be determined by repetitive iteration of the calculation until steady state. Bearing this in mind, the following design example shows how to estimate the power losses and junction temperature of NSF040120L4A0 in a bidirectional buck converter application with the design specifications shown below.

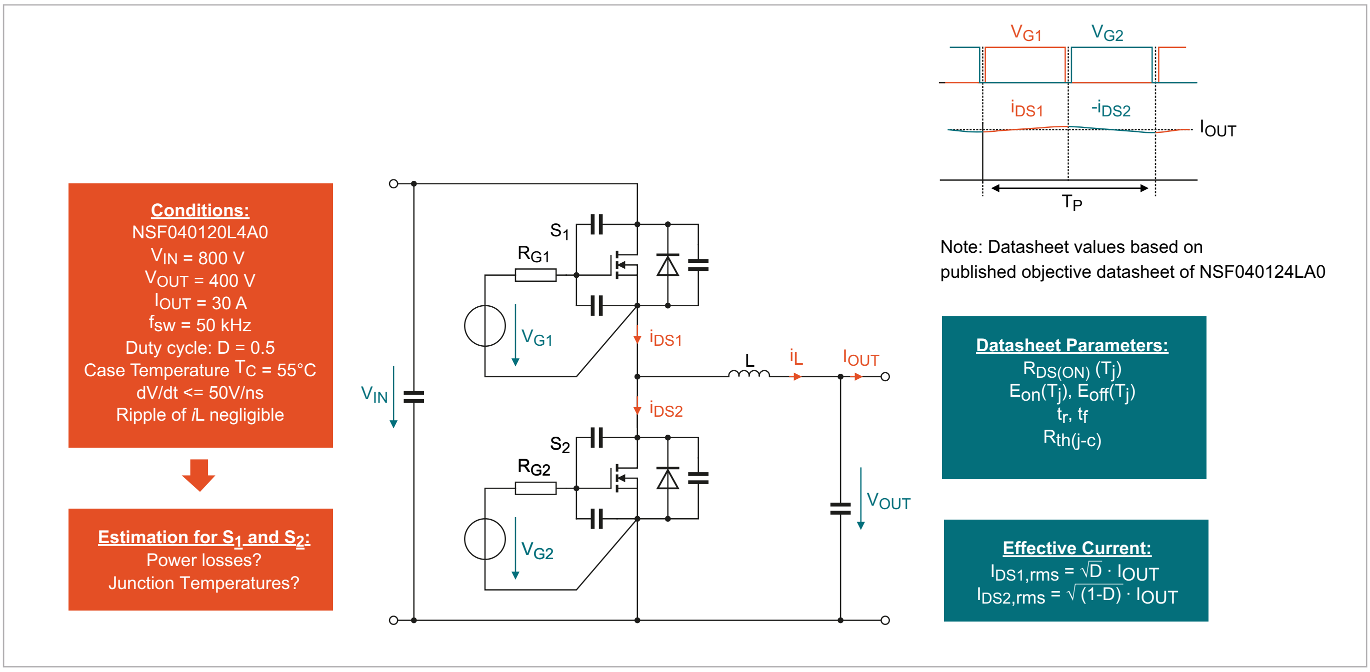


Figure 10 Design specifications for a bidirectional buck converter

Step 1: Conduction losses

To calculate conduction losses (P_c) for I_{out} = 30 A, the first step is to identify the temperature dependency of $R_{DS(on)}$ using the information provided in datasheet Fig. 4. Since only the values for I_{out} = 20 A and I_{out} = 40 A are shown in this graph, it is necessary to perform linear interpolation between these values as shown below. This allows the value of $R_{DS(on)}$ to be calculated for a specific drain current and junction temperature. Then, to determine conduction losses this must then be multiplied by the square of the root-mean-square (RMS) value for drain-source current ($I_{DS,rms}$).

Step 2: Switching losses

The definitions of switching losses and switching times are shown in Figure 11. In order to calculate switching losses, it is first necessary to select a reasonable external gate resistance $R_{G(ext)}$, which obeys the following conditions to satisfy EMC requirements:

- dV/dt = 50 V/ns
- ΔV_{DS} = 80%*VDC = 640 V (rise and fall times are calculated between 10% and 90% of VDC)

It can be observed from Fig.16 in the datasheet that the fall time t_f is always shorter than t_r, which means that dV/dt during turn-off is higher than the slope during turn-on by using the same $R_{G(ext)}$. Hence, to fulfil the dV/dt requirement, we only need to make sure dV/dt = $\Delta V_{DS}/t_f$ <=50 V/ns → t_f >= 12.8 ns.

Taking the trade-off between efficiency and EMC into consideration, $R_{G(ext)}$ = 10 Ω is adequate in this case, as shown in Figure 11.

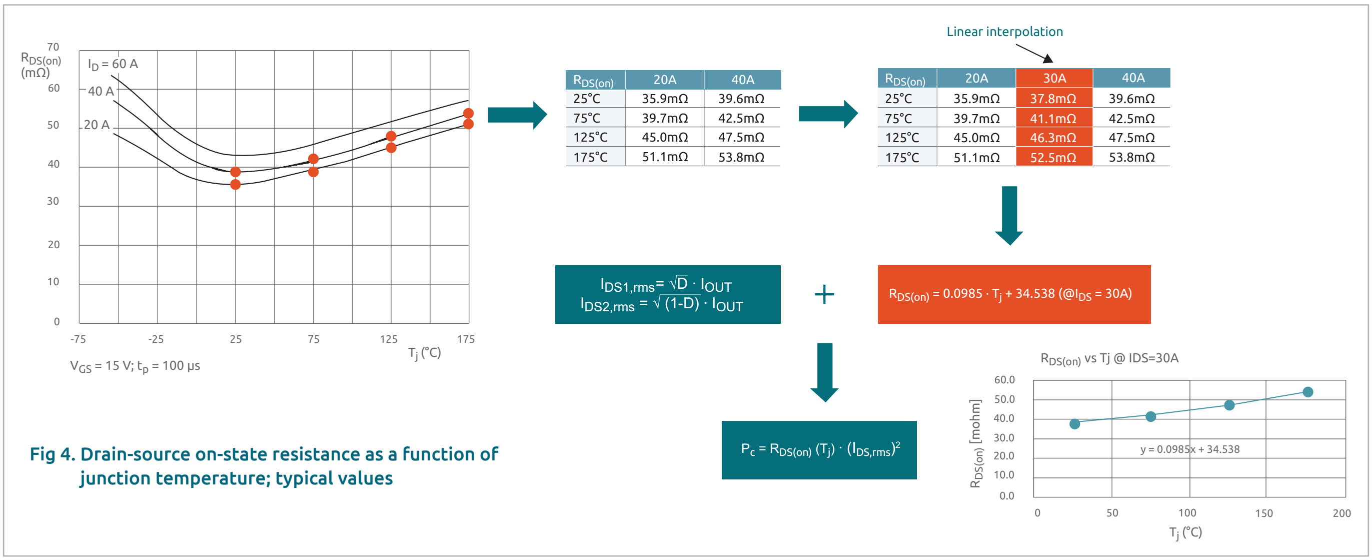


Fig 4. Drain-source on-state resistance as a function of junction temperature; typical values

$R_{DS(on)}$	20A	40A
25°C	35.9mΩ	39.6mΩ
75°C	39.7mΩ	42.5mΩ
125°C	45.0mΩ	47.5mΩ
175°C	51.1mΩ	53.8mΩ

Linear interpolation

$R_{DS(on)}$	20A	30A	40A
25°C	35.9mΩ	37.8mΩ	39.6mΩ
75°C	39.7mΩ	41.1mΩ	42.5mΩ
125°C	45.0mΩ	46.3mΩ	47.5mΩ
175°C	51.1mΩ	52.5mΩ	53.8mΩ

$R_{DS(on)} = 0.0985 \cdot T_j + 34.538$ (@I_{DS} = 30A)

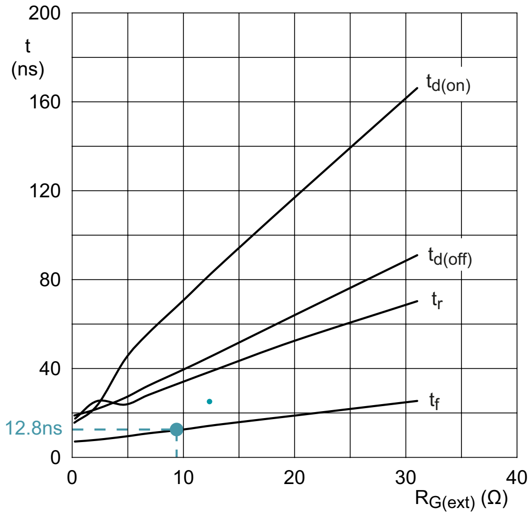
$I_{DS1,rms} = \sqrt{D} \cdot I_{OUT}$

$I_{DS2,rms} = \sqrt{(1-D)} \cdot I_{OUT}$

+

$P_c = R_{DS(on)}(T_j) \cdot (I_{DS,rms})^2$

Figure 11 Extracting current and temperature dependency of $R_{DS(on)}$ and calculating conduction losses



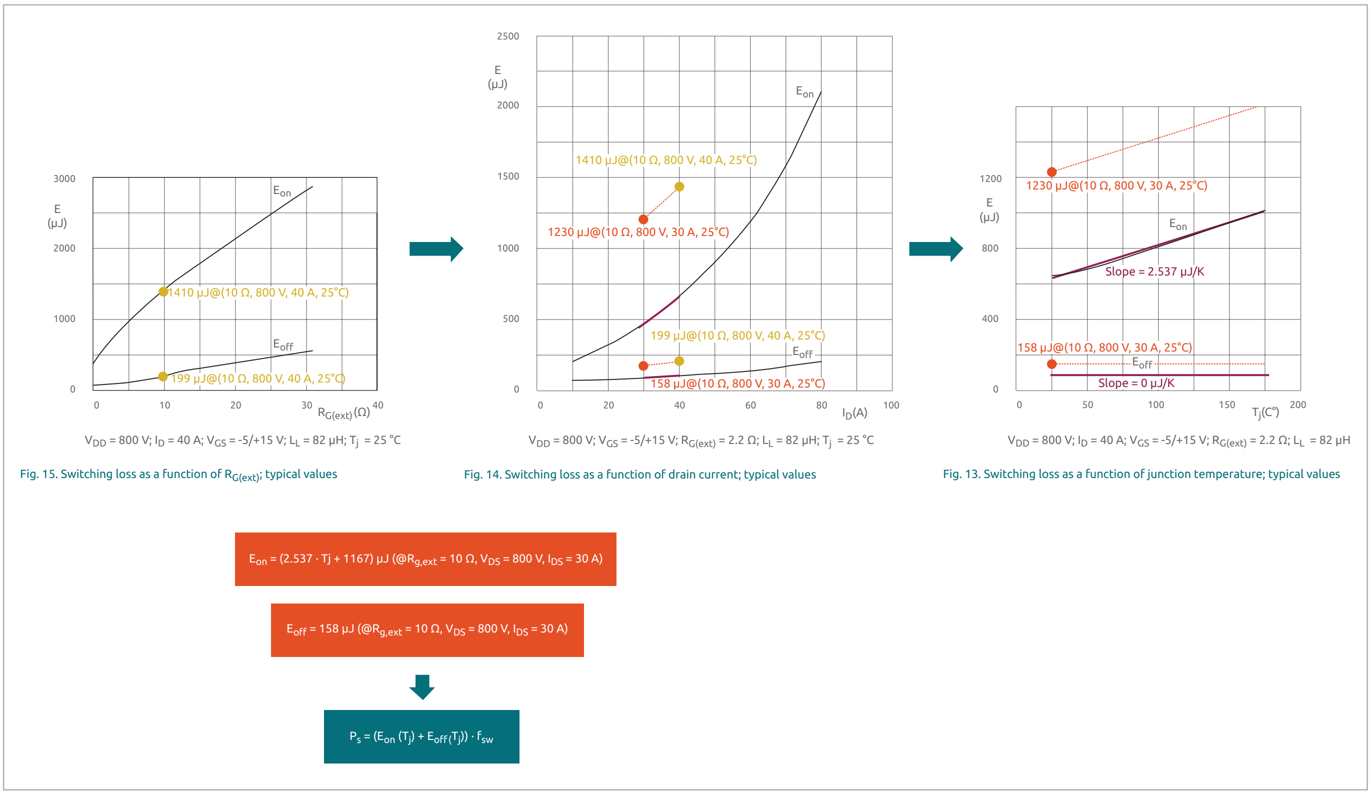
V_{DD} = 800 V; I_D = 40 A; V_{GS} = -5/+ 15 V; L_L = 82 µH;
T_j = 25 °C

Fig 16. Switching times as a function of $R_{G(ext)}$; typical values

Figure 12 Datasheet Fig. 16 shows how switching times are impacted by the value of external gate resistance

After determining the value of $R_{G(ext)}$, the temperature dependency of the switching losses at a given operating point can be deduced from the information provided by the Figs. 13, 14 and 15 in the datasheet as shown below.

It is important to note that the below calculations are based on the assumption that the load current ripple (ΔI_L) is negligible. If this is not the case, then the calculations for conduction and switching losses must be modified as shown in Figure 14.



V_{DD} = 800 V; I_D = 40 A; V_{GS} = -5/+15 V; L_L = 82 µH; T_j = 25 °C

Fig. 15. Switching loss as a function of $R_{G(ext)}$; typical values

V_{DD} = 800 V; V_{GS} = -5/+15 V; $R_{G(ext)}$ = 2.2 Ω; L_L = 82 µH; T_j = 25 °C

Fig. 14. Switching loss as a function of drain current; typical values

V_{DD} = 800 V; I_D = 40 A; V_{GS} = -5/+15 V; $R_{G(ext)}$ = 2.2 Ω; L_L = 82 µH

Fig. 13. Switching loss as a function of junction temperature; typical values

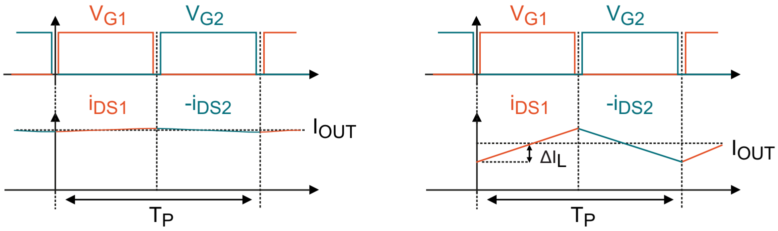
E_{on} = (2.537 · Tj + 1167) µJ (@$R_{g,ext}$ = 10 Ω, V_{DS} = 800 V, I_{DS} = 30 A)

E_{off} = 158 µJ (@$R_{g,ext}$ = 10 Ω, V_{DS} = 800 V, I_{DS} = 30 A)

$P_s = (E_{on}(T_j) + E_{off}(T_j)) \cdot f_{sw}$

Figure 13 Datasheet Figs. 13,14 and 15 can be used to calculate switching losses

$$I_{DS,rms} = \sqrt{\frac{1}{T_P} \bullet \int_0^{T_P} (i_{DS})^2 dt}$$



Thermal characteristics

		ΔI_L negligible	ΔI_L not negligible
Conduction losses	$I_{DS1,\,rms}$	$\sqrt{D} \cdot I_{OUT}$	$\sqrt{D} \cdot \sqrt{I_{OUT}{}^2 + \frac{\Delta I_L^2}{3}}$
	$I_{DS2,\,rms}$	$\sqrt{(1-D)} \cdot I_{OUT}$	$\sqrt{(1-D)} \cdot \sqrt{I_{OUT}{}^2 + \frac{\Delta I_L^2}{3}}$
Switching losses	i_{DS} at turn-on	I_{OUT}	$I_{OUT} - \Delta I_L$
	i_{DS} at turn-off	I_{OUT}	$I_{OUT} + \Delta I_L$

Figure 14 Equations for calculating conduction and switching losses

Conclusion

The ever increasing number of applications for SiC MOSFETs can make it difficult for engineers to interpret which datasheet parameters have the greatest impact on power losses, system efficiency and device junction temperature in their circuits. This knowledge is required in order to compare and contrast the performance of devices from different manufacturers and determine which is best for a specific application. In this white paper, Nexperia explored critical datasheet parameters for its recently introduced NSF040120L4A0 SiC MOSFET and demonstrated how these parameters can be applied to support design-in decisions for a widely used bidirectional DC-DC buck converter application. It also demonstrated how to estimate the junction temperature and power losses of power semiconductor devices using datasheet information.

About Nexperia

Headquartered in the Netherlands, Nexperia is a global semiconductor company with a rich European history and over 14,000 employees across Europe, Asia, and the United States. As a leading expert in the development and production of essential semiconductors, Nexperia's components enable the basic functionality of virtually every electronic design in the world – from automotive and industrial to mobile and consumer applications.

The company serves a global customer base, shipping more than 100 billion products annually. These products are recognized as benchmarks in efficiency – in process, size, power and performance. Nexperia's commitment to innovation, efficiency and stringent industry requirements are evident in its extensive IP portfolio, its expanding product range and its certification to IATF 16949, ISO 9001, ISO 14001 and ISO 45001 standards.

Find your regional sales office here

nexperia.com

Date of release:
May 2024