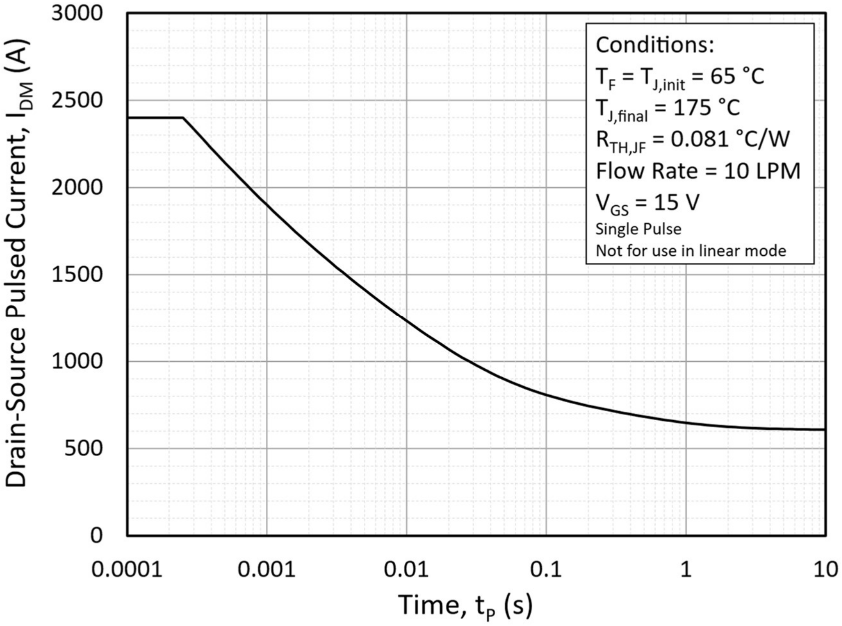
Application Note **PRD-09597**

Introduction to Pulsed Current Safe Operating Area



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Introduction to Pulsed Current Safe Operating Area

The pulsed current safe operating area (SOA) plot is defined, and its calculations are detailed in this document. Pulsed Current SOA is primarily dependent on the transient thermal impedance. Transient thermal impedance is critical to understanding a semiconductor's thermal performance over time and can be used to determine the operational limits and possible performance in a given application. The steps to use the transient thermal impedance to estimate junction temperature (T_J) for given operating conditions are explained through examples in this document.

Contents

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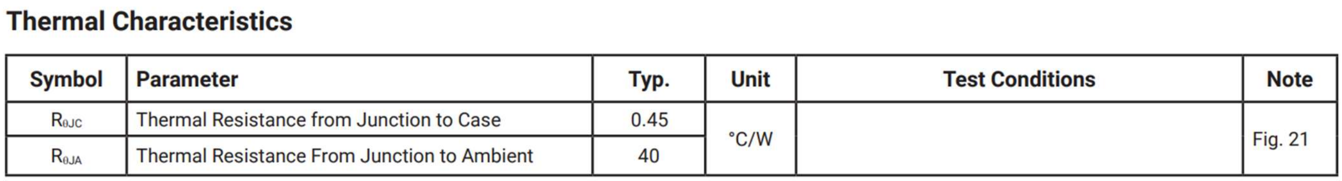
1. Introduction

This application note defines and describes the correct usage of the Pulsed Current SOA plot published in Wolfspeed MOSFET datasheets. Additionally, it explains the difference between **static** thermal resistance ($R_{TH,JC}$) and **transient** thermal impedance ($Z_{th,JC}$) with the help of examples. While this document provides a basic introduction to thermal impedance, much greater detail can be found in **PRD-08376** [1].

Absolute maximum ratings of the devices should not be exceeded, especially the maximum junction temperature, $T_{J,max}$, as this will degrade lifetime and reliability of the device as well as increase the risk of thermal runaway. This application note provides the definitions and background to determine safe operation from the thermal impedance for a given application and how this analysis can be extended to build the pulsed current SOA figure.

2. Static Thermal Resistance

The 'Thermal Characteristics' tables in MOSFET datasheets (example table shown in Figure 1) provides single point data for static thermal resistance from junction to case ($R_{\theta JC}$ or $R_{TH,JC}$ used interchangeably) and static thermal resistance from junction to ambient ($R_{\theta JA}$).

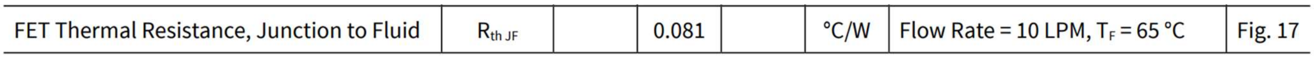


Thermal Characteristics

Symbol	Parameter	Typ.	Unit	Test Conditions	Note
$R_{\theta JC}$	Thermal Resistance from Junction to Case	0.45	°C/W		Fig. 21
$R_{\theta JA}$	Thermal Resistance From Junction to Ambient	40			

Figure 1: Thermal resistance table for C3M0032120K

While thermal resistance is typically defined in terms of the semiconductor junction and case, this is not the most relevant parameter for every package technology. For example, Wolfspeed modules with integrated liquid cooling pins have their thermal resistance defined in terms of junction to fluid, such as shown in Figure 2.



FET Thermal Resistance, Junction to Fluid	$R_{th\ JF}$		0.081		°C/W	Flow Rate = 10 LPM, T_F = 65 °C	Fig. 17

Figure 2: Thermal resistance table for ECB2R1M12YM3

Table 1 gives an overview of the various definitions used in Wolfspeed Datasheets.

Table 1: Thermal resistance definitions

Symbol	Definition	Example Part Numbers
$R_{TH,JC}$	Junction to Case	**C3M0032120K**, **EAB450M12XM3**
$R_{TH,JH}$	Junction to Heatsink	**CAB011M12FM3**, **CAB5R0A23GM4**
$R_{TH,JF}$	Junction to Fluid	**CAB525F12XM3**, **ECB2R1M12YM3**

These various definitions are appropriate depending on the package technology of the part.

Junction to Case, $R_{TH,JC}$: the standard definition used for all discrete MOSFETs and diodes as well as most power modules

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Junction to Heatsink, $R_{TH,JH}$: used in WolfPACK™ module datasheets. Because these modules do not have a baseplate, the thermal impedance definition includes the case to heatsink thermal impedance, $R_{TH,CH}$, which is equivalent to the impedance of the thermal interface material (TIM), $R_{TH,TIM}$. The relationship between junction to heatsink and junction to case is defined by,

$$R_{TH,JH} = R_{TH,JC} + R_{TH,CH} \tag{1}$$

$$R_{TH,CH} = R_{TH,TIM} \tag{2}$$

Junction to Fluid, $R_{TH,JF}$: for modules with integrated pin fin cooling, thermal impedance can be defined in terms of the fluid, giving a more accurate representation of system performance (at a given flowrate). While the $R_{TH,JC}$ can be measured for such modules, this parameter is not relevant to real world use; the system designer can predict fluid temperature, while case temperature is generally irrelevant (in cases requiring T_C, Wolfspeed recommends using the simplifying assumption that case and fluid temperature are equal).

3. Transient Thermal Impedance

The transient thermal impedance models the thermal resistance and energy storage (i.e. thermal mass or capacitance) of the package in response to transient heat transfer events. The instantaneous thermal impedance is dependent on pulse width in single pulse occurrence as well as duty cycle in continuous pulse operation. The plot of $Z_{TH,JC}$ indicates the heat dissipation capability of the device and package from junction to case.

Figure 3 shows an example of a transient thermal impedance curve, plotted as a function of pulse time (t_P). The single pulse thermal impedance can be represented as a thermal equivalent circuit (TEC) of resistors and capacitors in either a Foster or Cauer configuration. As the pulse time increases, the thermal dissipation stabilizes to a final value of $R_{TH,JC}$, the settling time is dependent on the thermal mass of the system but usually is greater than a second. For times shorter than 1 s, $Z_{TH,JC}$ is a more accurate representation of the power the device can dissipate.

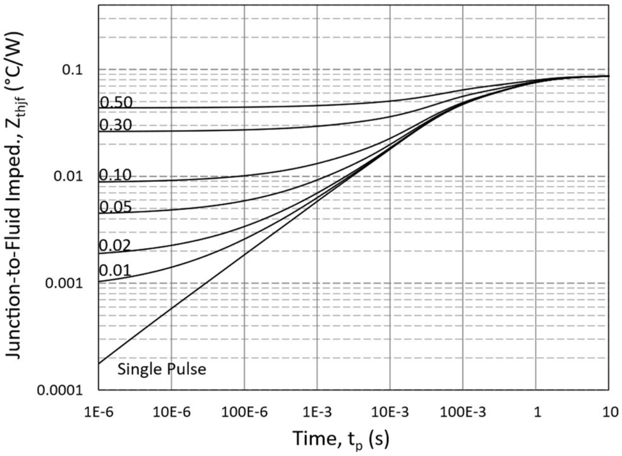

Figure 3: Transient thermal impedance for ECB2R1M12YM3

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3.1 JEDEC Definitions

Transient thermal impedance is a critical parameter for understanding the thermal characteristics of a semiconductor. The technical terminology relevant to transient thermal impedance is defined in detail in this section. Where applicable, relevant JEDEC standards are also referenced.

Steady-State Thermal Resistance – Junction to Case, $R_{TH,JC}$: **(JESD51-1)** the thermal resistance from the operating portion of a semiconductor device to outside surface of the package (case) closest to the chip mounting area when that same surface is properly attached to a heat sink to minimize temperature variation across that surface.

$$R_{\theta,JC} = \frac{T_J - T_C}{P_H} \tag{3}$$

T_J is the steady-state junction temperature, T_C is the case temperature for the specified environmental conditions and P_H is the power dissipated in the device. T_{J0} is the initial junction temperature and ΔT_J is the change in junction temperature due to power dissipation.

$$T_J = T_{J0} + \Delta T_J \tag{4}$$

Transient Thermal Impedance – Junction to Case, $Z_{TH,JC}$: **(JESD51-1)**: a measure of the transient heat flow restrictions from a point of high temperature to a point of lower temperature. **(JESD88E):** The change in temperature difference between two specified points or regions (junction and case in this case) that occurs during a time interval divided by the step-function change in power dissipation that occurred at the beginning of the interval and caused the change in temperature difference. In simpler terms, thermal impedance equals the time-dependent change of the junction temperature T_J (t) divided by the heating power.

$$Z_{TH,JC}(t) = \frac{T_J(t) - T_J(t_0)}{P_H} \tag{5}$$

Pulse Time, t_P: The duration during which the current is applied to the MOSFET. The transient thermal impedance is a function of the pulse time of the current.

3.2 Reading the Thermal Impedance Plot

The transient thermal impedance plot in Wolfspeed MOSFET datasheets show junction-case thermal impedance ($Z_{TH,JC}$ in K/W) as a function of pulse time (t_P in seconds). It defines the rise in temperature for a given transient power dissipation and can be used to calculate the thermal impact of transient from the device's thermal performance.

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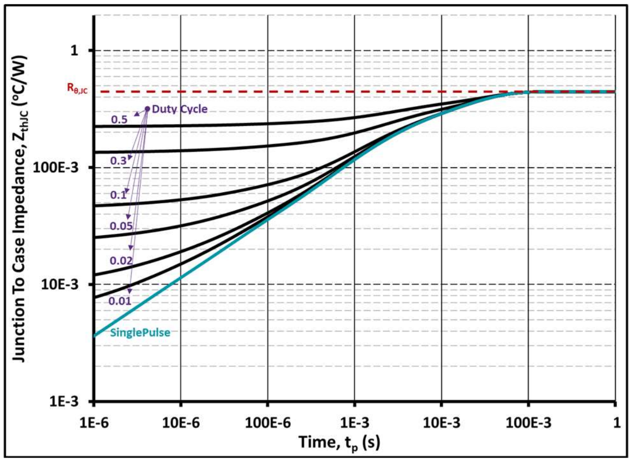

Figure 4: Annotated thermal impedance plot

The curves in this plot come from the model generated by the typical part measurement. Typically cooling curves are measured with T_J reaching 100°C, cooling to 25°C.

Figure 4 highlights various elements within the thermal impedance plot. The single pulse curve is shown in teal and is measured with a single pulse applied to the device to measure $Z_{TH,JC}$. The other series of black lines denote the data for continuous pulses at various duty cycles. For larger pulse times, where the curves converge, is the steady-state $Z_{TH,JC}$ for the device, which is equivalent to the static $R_{TH,JC}$.

3.3 Extracting $Z_{TH,JC}$ Value

Consider a C3M0032120K MOSFET being used in an application. The following examples (Figure 5) illustrate how a designer can extract the $Z_{TH,JC}$ values from the plot for different cases. The cases discussed below and shown in Figure 5 are for different current pulse conditions, with each circle labeled in the figure with its respective case number. The values in the plot are for a typical MOSFET as well as typical values of T_J and ambient temperature (T_{amb}).

Case 1: DC conduction through the device: $Z_{TH,JC} = R_{TH,JC} = 0.45$ K/W

Case 2: Single pulse current passed through the device, with a pulse width of 100 µs: $Z_{TH,JC} = 0.034$ K/W

Case 3: Current pulsed continuously through the device with a pulse width of 10 µs, duty cycle = 0.3 (on time = 3 µs, off time = 7 µs): $Z_{TH,JC} = 0.14$ K/W

Case 4: Single pulse current passed through the device, with a pulse width of 10 ms: $Z_{TH,JC} = 0.2896$ K/W

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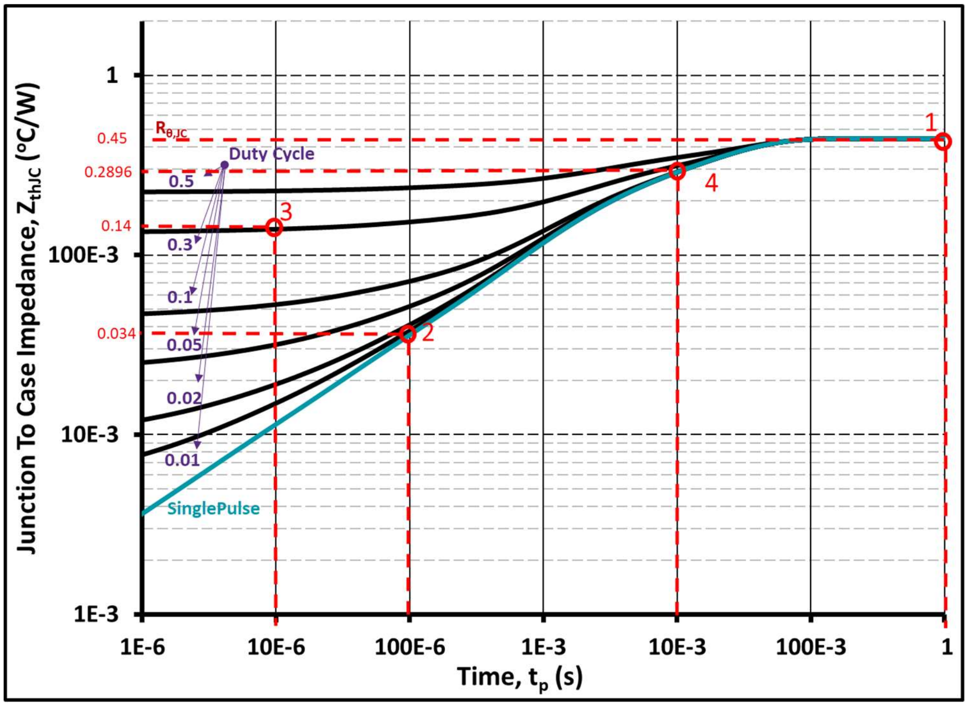

Figure 5: $Z_{TH,JC}$ value extraction

3.4 Application Implications

This section focuses on the foundations of thermal calculations using static and thermal impedances. Examples are given to show ways to use the datasheet plots and when should either of the parameters be used for calculations.

Example 1:

A buck converter has the following specifications, as shown in the image below. Let us assume that we are using a C3M0032120K MOSFET and the case temperature of the device is fixed at 65°C. SpeedFit™ Design Simulator has been used here to support the analysis with a simulation example.

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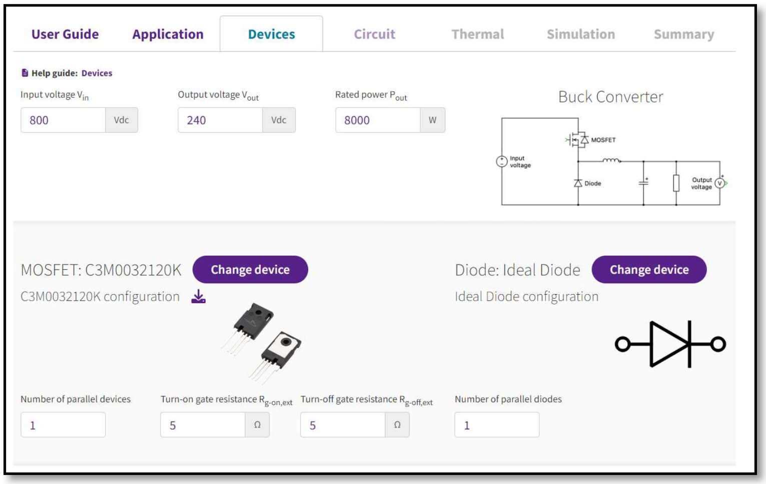


Input voltage V_{in}: 800 Vdc

Output voltage V_{out}: 240 Vdc

Rated power P_{out}: 8000 W

MOSFET: C3M0032120K

C3M0032120K configuration

Diode: Ideal Diode

Ideal Diode configuration

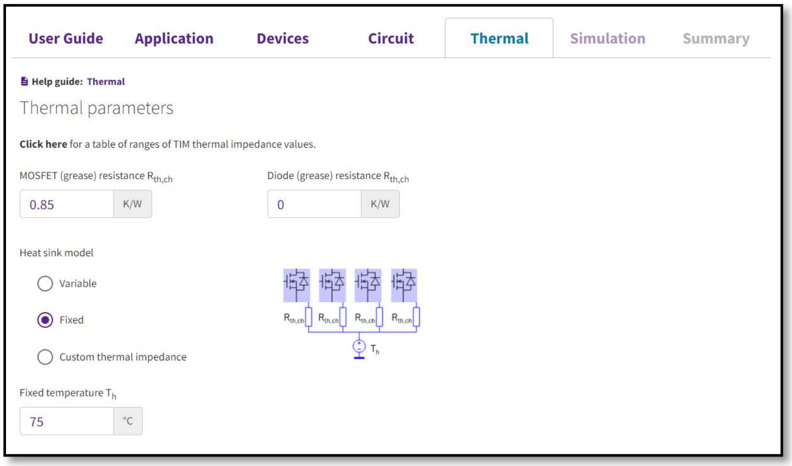
Number of parallel devices: 1

Turn-on gate resistance $R_{g\text{-}on,ext}$: 5 Ω

Turn-off gate resistance $R_{g\text{-}off,ext}$: 5 Ω

Number of parallel diodes: 1

Figure 6: Buck converter simulation on SpeedFit: topology specification and device selection



Thermal parameters

Click here for a table of ranges of TIM thermal impedance values.

MOSFET (grease) resistance $R_{th,ch}$: 0.85 K/W

Diode (grease) resistance $R_{th,ch}$: 0 K/W

Heat sink model

○ Variable

● Fixed

○ Custom thermal impedance

Fixed temperature T_h: 75 °C

Figure 7: Thermal specification for SpeedFit™ simulation

After calculating or deriving the losses in a device, T_J can be calculated such as a function of average power dissipation in the device over the period after the converter achieves steady state operation. We will refer to the thermal resistance values for the **C3M0032120K**. The power dissipation value is taken from SpeedFit^{TM} results, as shown in Figure 8. In the same figure, we can see that the average junction temperature is equal to the $T_{J,avg}$ calculated in Equation (6) below.

$$T_{J,avg} = P_{H,avg} * \left(R_{TH,JC} + R_{TH,CH}\right) = 25.96\ \mathrm{W} * (0.45 + 0.85)\ {}^{\circ\mathrm{C}}/_{\mathrm{W}} + 75^{\circ}\mathrm{C} = 108.8^{\circ}\mathrm{C} \qquad (6)$$

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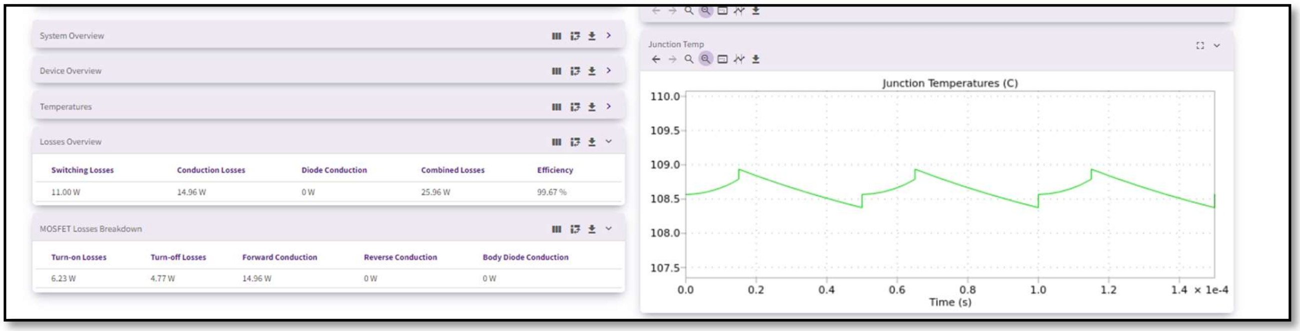

Switching Losses	Conduction Losses	Diode Conduction	Combined Losses	Efficiency
11.00 W	14.96 W	0 W	25.96 W	99.67 %

Turn-on Losses	Turn-off Losses	Forward Conduction	Reverse Conduction	Body Diode Conduction
6.23 W	4.77 W	14.96 W	0 W	0 W

Figure 8: Simulation results and waveforms for junction temperature

Junction temperature varies over the period as a function of power dissipated in the device, therefore, $T_{J,max}$ would be higher than the average T_J. $T_{J,avg}$ is the steady-state junction temperature averaged over the time period.

Power dissipation in a device varies periodically with switching frequency. Therefore, instantaneous junction temperature will also vary periodically with time as a function of instantaneous power dissipation. To find the maximum junction temperature of a device, the rise in temperature due to ripple in power dissipation is required to be added the average junction temperature. Calculating the instantaneous rise due to a single or repeating pulse requires the dynamic thermal impedance value. However, $T_{J,max}$ calculation in continuous operation is challenging to perform on paper. In such situations, simulators like SpeedFit, PLECS and SPICE can quickly estimate parameters such as $T_{J,max}$, in addition to voltage, current and power stress on the device for verifying safe operation of the device. For brief transient simulations (<100 ms) SPICE can provide a detailed insight into MOSFET behavior, while, due to its much higher simulation speed, PLECS is an excellent tool for longer simulations and predicting steady-state performance.

Example 2:

Device is operating under certain conditions and suddenly a surge of 10 ms occurs at the device with $T_{J,initial} = 90°C$. From equation (5):

$$T_J(t) = Z_{TH,JC}(t) * P_H + T_J(t_0) \qquad (7)$$

For C3M0032120K, we know that the thermal impedance at 10 ms pulse width for a single pulse is 0.2896 K/W (Case 4 from Section 3.3). Using this information, investigation for safe operation can be carried out in the following two ways:

a) Find $T_{J,final}$ when a single pulse of 55 A flows through the device for 10 ms.

$I_{D(pulse)} = 55$ A, $t_P = 10$ ms;

From datasheet: $R_{DS(on)}(T_J = 175°C) = 57.6$ mΩ.

The power dissipation during forward conduction (first-quadrant operation) can be estimated by:

$$P_H = I^2 * R_{DS(on)}(T_J = 175°C) \qquad (8)$$

Using substituting (8) for P_H in (7), junction temperature can be calculated:

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$$T_J\ (t) = 0.2896\ \mathrm{K/W} * (55\ \mathrm{A} * 55\ \mathrm{A} * 0.0576\ \mathrm{m\Omega}) + 90°\mathrm{C} = \ 140°\mathrm{C} \tag{9}$$

Since $T_{J,final} < 175°C$ the device is safe to operate.

The choice of $R_{DS(on)}$ at $T_J = 175°C$ is a conservative approach because it assumes maximum power dissipation. If users would like better accuracy, it is recommended to reiterate the process using $R_{DS(on)}$ at the calculated T_J (140°C in the current example). After a few reiterations, the max temperature can be settled.

b) Find maximum amplitude for current pulse such that $T_J < 175°C$, for the given pulse width

From equation (8): $P_H = (175°C - 90°C) / 0.2896\ K/W = 293.5\ W$

From the datasheet: $R_{DS(on),max} = 57.6\ m\Omega$

$$I_D = \sqrt{\frac{P_H}{R_{DS,on}(T_J = 175°C)}} = \sqrt{\frac{293.5}{0.0576}} = 71.4\ A \tag{10}$$

The device can safely carry 71.4 A (or less) for 10 ms without reaching $T_{J,max}$. Of course, since the initial temperature of the device is not 175°C, assuming that $R_{DS(on)}$ is the maximum value for the entire pulse duration is not correct, leading to a slight underestimation of the maximum current that sustained without exceeding $T_{J,max}$.

Additionally, this maximum current vs pulse width is not a direct calculation of short circuit withstand time, because:

(1) Assuming conduction losses are equal to I^2R is incorrect for short circuit conditions, as the drain-source voltage will be higher than the nominal resistance, leading to an underestimation of power dissipation.

(2) Short circuit withstand time is not determined by instantaneous excursions above $T_{J,max}$ (i.e. the MOSFET will not instantaneously fail when $T_{J,max}$ is exceeded). Instead, the pulse current limit here provides a more conservative limit which minimizes device degradation by never leaving the SOA.

4. Pulsed Current Safe Operating Area

Consider the outcome from the previous example: for any pulse time and case temperature, it is possible to calculate the current that will cause the maximum temperature to reach 175°C. Since this is possible for any pulse time, it is also possible to calculate it across all pulse times. By inverting (5),

$$P_H = \frac{T_{J,final} - T_{J,initial}}{Z_{TH}} \tag{11}$$

If P_H is calculated for every single pulse value of Z_{TH}, a new plot can then be created of the maximum instantaneous power that can be dissipated for a given pulse width, initial temperature, and final temperature. An example of this plot is given in Figure 9 for the ECB2R1M12YM3 power module.

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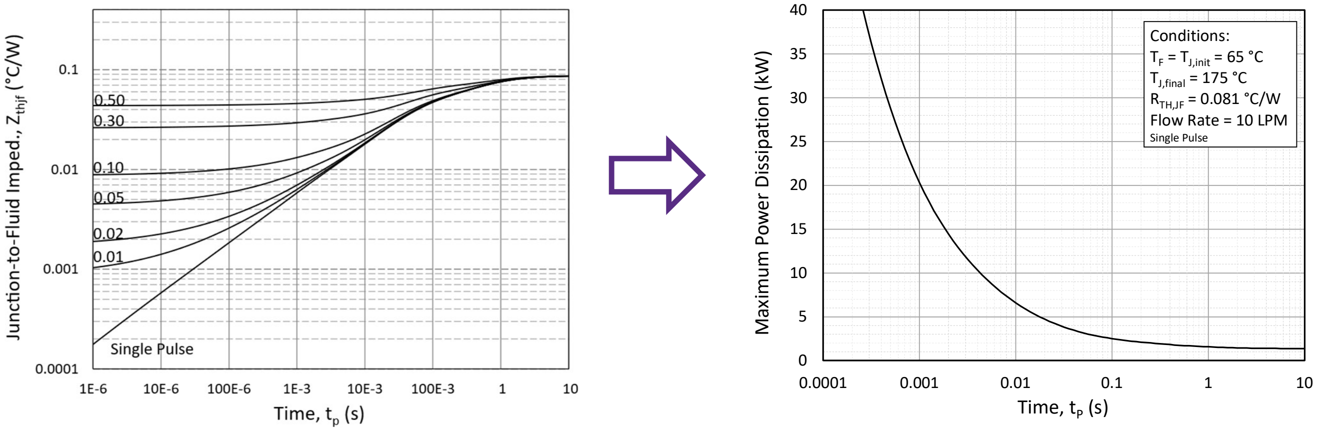

Figure 9: Maximum instantaneous power dissipation, ECB2R1M12YM3

While this maximum power dissipation is somewhat useful as a design constraint, a more intuitive representation is to present the current limitation created by the power limit using the relationship between current and power loss. The formula given in (8) can be used to determine this relationship, however, the assumption that $R_{DS(on)}$ is fixed for a given temperature is only acceptable for loose approximations. In reality, the voltage drop from drain to source is highly dependent on the test current, especially at higher junction temperatures, as demonstrated in Figure 10.

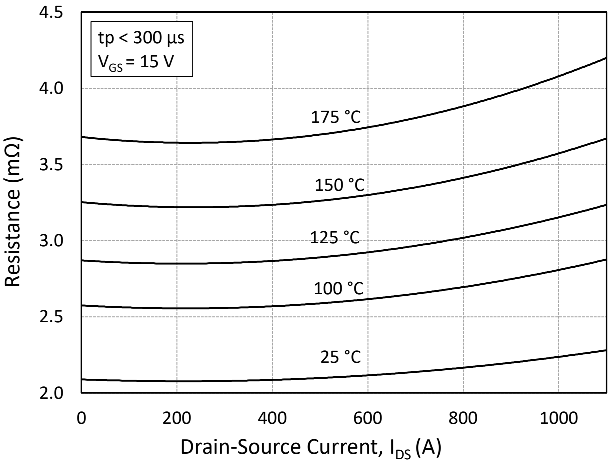

Figure 10: Resistance vs current at various operating temperatures, ECB2R1M12YM3

A more precise estimate of conduction loss versus current can be created using resistance at each current value. Figure 11 shows the widening delta between the nominal estimation and the precise estimation as current increases.

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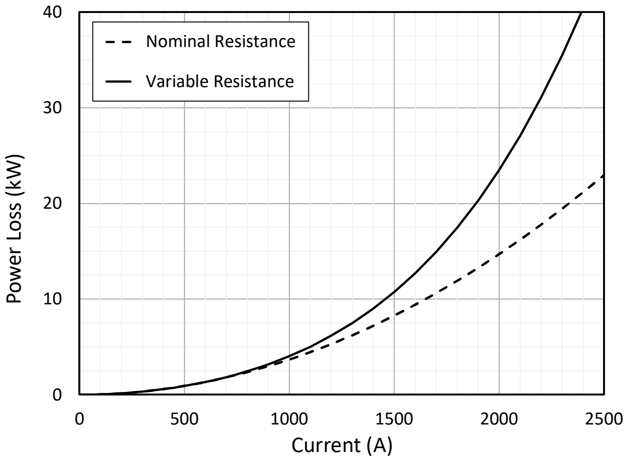

Figure 11: DC Power loss versus current at 175°C, ECB2R1M12YM3

This relationship for power versus current assumes that the temperature is fixed at 175°C. It also assumes that the device is fully gated on (V_{GS} = +15 V or +18 V per the datasheet), as it is not recommended to use Wolfspeed SiC MOSFETs in the linear region (operation in linear region can lead to thermal runaway due to local current concentration in the MOSFET). Similarly, the DC power losses are calculated considering continuous MOSFET forward operation and do not consider third quadrant or body diode losses.

With a relationship for maximum power versus time (Figure 9) and conduction loss versus current (Figure 11), calculating the relationship for current versus time simply requires finding the intersection between the two previous lines. Figure 12 shows the curve which is derived from this intersection: the maximum current, $I_{DM(pulse)}$, as a function pulse time, t_P.

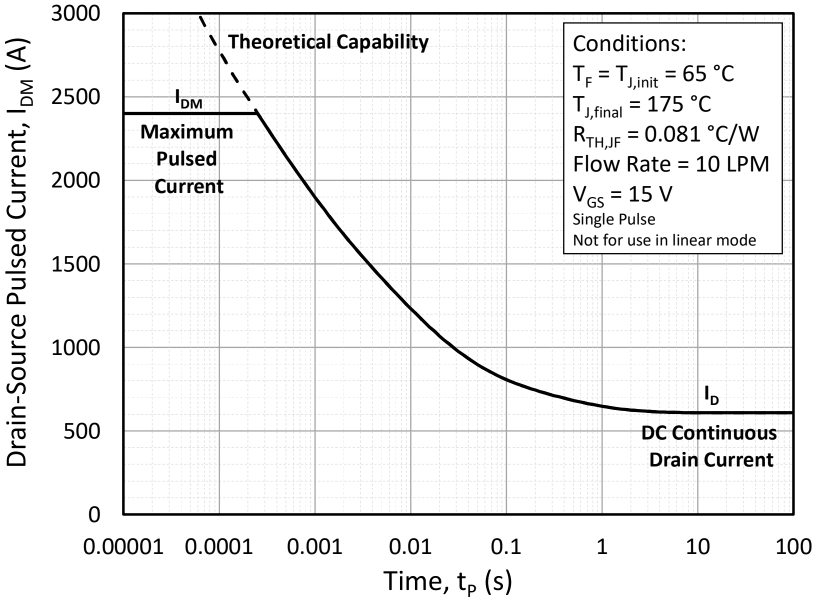

Figure 12: Annotated pulsed current SOA, ECB2R1M12YM3

While the pulsed current SOA curve is derived from the power and loss relationship described above, at large pulse times (where $Z_{TH,JC} = R_{TH,JC}$), the calculation of pulsed current is equivalent to the calculation of maximum

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continuous DC drain current, I_D, as described in the maximum parameter table of the datasheet. Similarly, at very small pulse times, the calculated current can exceed the maximum pulsed drain-source current, I_{DM}, defined in the maximum parameter table of the datasheet. Unlike the pulsed current SOA plot, I_{DM} is not defined by $T_{J,max}$, instead determined to meet device reliability requirements. Therefore, at small timesteps, the value of pulsed current SOA is limited by the value provided in the maximum parameter table.

While hitting the maximum junction temperature of the MOSFET is typically the only concern when determining SOA, in rare cases, the package can limit the pulsed current capability of the MOSFET. For example, in the FM3 six-pack modules CCB021M12FM3 and CCB032M12FM3, the press-fit pins limit the DC continuous current, as shown in Figure 13.

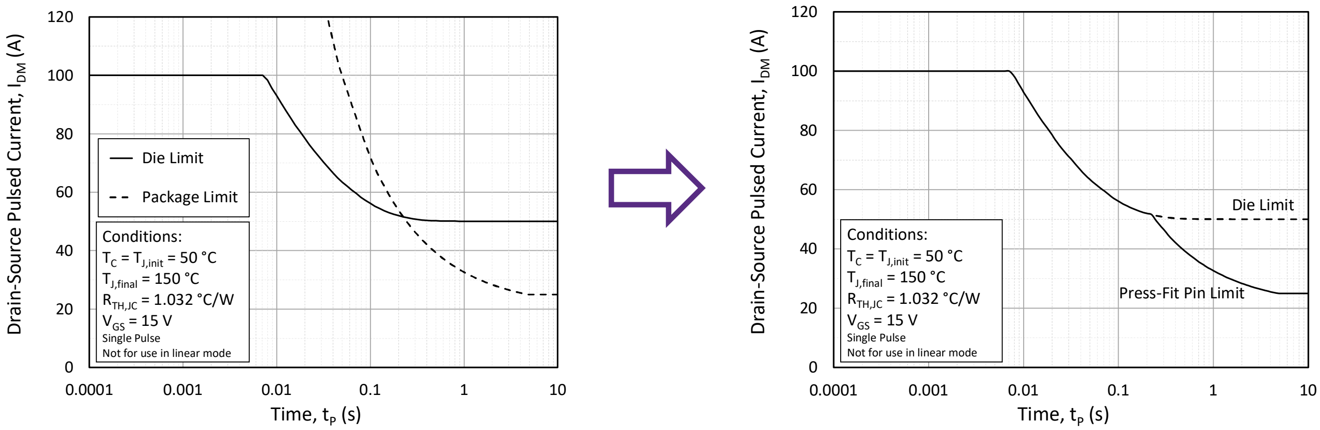

Figure 13: Packaging pulsed current limit, CCB021M12FM3

While the press-fit pins limit the maximum continuous current of the module, their current limit is also dependent on the length of the current pulse. Therefore, the relationship for the maximum current of the pins versus time was created and plotted against the pulsed current maximum of the die. Because of the relatively high thermal mass of the pins, the time required to reach steady state temperature was longer on average than the die. Therefore, the maximum pulse current is defined by the minimum of the die and package limits.

5. Conclusion

This application note covers the foundational concepts, equations, and definitions needed for designers to interpret the thermal impedance and pulsed current SOA plots on Wolfspeed MOSFET datasheets. Various examples are also given in this app note to show how thermal calculation for safe operation can be used for analytical calculations.

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Revision History

Date	Revision	Changes
October 2025	1	Initial Release

References

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