Thermal Design

Notes for Calculating Power Consumption: Static Operation

If a circuit such as a power supply that generates a large power consumption is designed, it is confirmed with a simulation or calculation that the junction temperature in devices including MOSFET will not exceed the absolute maximum rating. Using inappropriate parameters in this simulation or calculation may result in incorrect design values. This application note provides precautions for the parameters to be used in power consumption calculations involving the thermal design.

Calculation formula for the junction temperature

As shown in Equation 1, the junction temperature of MOSFET is generally calculated by multiplying the thermal resistance from the junction to the ambient temperature by the power consumption of the device, and then adding the ambient temperature to the product. As shown in Figure 1, the thermal resistance from the junction to the ambient temperature consists of the thermal resistance from the junction to the case, the contact thermal resistance from the case including the thermal interface material (TIM) to the heat sink, and the thermal resistance from the heat sink to the ambient temperature.

$$T_J = \left(R_{thJC} + R_{thCH} + R_{thHA} \right) \times P_D + T_A \quad [\text{°C}] \quad (1)$$

R_{thJC}: Thermal resistance from the junction to the case [°C/W]

R_{thCH}: Thermal resistance from the case to the heat sink [°C/W]

R_{thHA}: Thermal resistance from the heat sink to the ambient temperature [°C/W]

P_D: Power consumption of the device [W]

T_A: Ambient Temperature [°C]

Precautions for the parameters to be used

Methods of calculating the power consumption of devices depend on the circuit operations. For simplicity, the calculation is explained here for the static operation without any switching operation.

The power consumption when the MOSFET is ON can be calculated from the conduction loss, which is calculated by multiplying the square of the drain current by the drain-source on-resistance as shown in Equation 2.

$$P_D = I_D^2 \times R_{DS(on)} \quad [W] \quad (2)$$

I_D: Drain current [A]

$R_{DS(on)}$: Drain-source on-resistance [Ω]

Refer to the value in the data sheet for $R_{DS(on)}$. Use the maximum value at the junction temperature instead of the standard value at 25°C. If such a maximum value is not used, the junction temperature may be underestimated, leading to incorrect results.
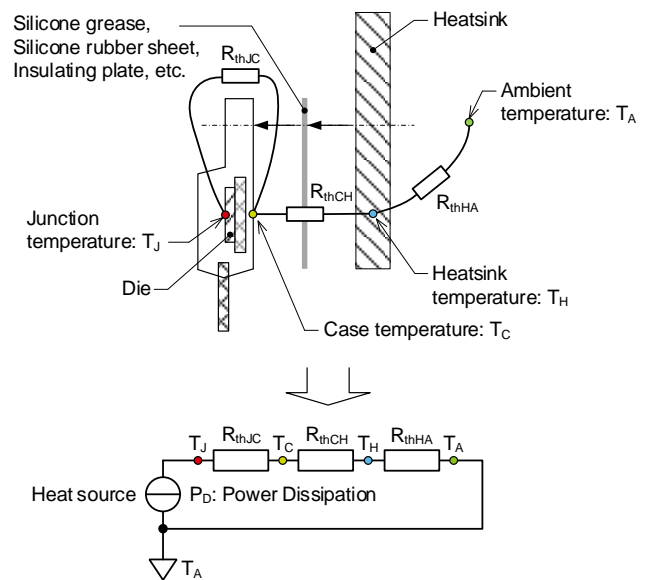

Figure 1. Heat dissipation equivalent circuit

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Method of calculating the junction temperature

This section explains the method of calculating the junction temperature graphically. As an example, the data sheet for N-channel SiC power MOSFET SCT4036KR is used.

First, prepare the parameter values required for the calculation. The following values are used in this example.

$I_D = 17 \,[A]$

$R_{DS(on)}$: To be calculated.

$R_{thJC} = 0.85 \,[ºC/W]$ (from the data sheet)

$R_{thCH} = 0.67 \,[ºC/W]$

$R_{thHA} = 1.48 \,[ºC/W]$

$T_A = 65 \,[ºC]$

For R$_{thJC}$, use the maximum value provided in the data sheet (Figure 2).

● Thermal resistance

Parameter	Symbol	Values			Unit
		Min.	Typ.	Max.	
Thermal resistance, junction - case	R$_{thJC}$ *9	-	0.65	0.85	K/W

Figure 2. Standard value of R$_{thJC}$ in the data sheet
Use the maximum value

Junction temperature T$_J$ is calculated with Equation 1. However, the R$_{DS(on)}$ value at the junction temperature must be used to calculate P$_D$. Since T$_J$ is unknown at this point, it is impossible to determine the temperature at which the R$_{DS(on)}$ value should be used. Therefore, first prepare the maximum values of R$_{DS(on)}$ at different temperatures.

Figure 3 shows the graph provided in the data sheet showing R$_{DS(on)}$ as a function of the junction temperature. Use digitizer software or the like to read the values.
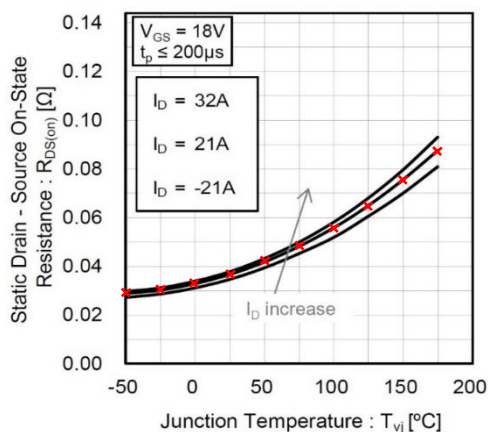

Figure 3. Graph provided in the data sheet showing R$_{DS(on)}$ as a function of the junction temperature

As shown in Figure 4, use Excel to create a graph from the read values. Add a trendline and display the approximation equation.

Calculate the maximum values from the standard values shown in this graph. As shown in Figure 5, the standard for the on-resistance is provided in the data sheet. In this example, since the standard value is 36mΩ and the maximum value is 47mΩ, the ratio is 1.3056. Next, use the approximation equation above to calculate the on-resistance at each temperature, and then multiply the value by 1.3056 to calculate the maximum value of the on-resistance. Calculate the high temperature part only, because the calculation for the low temperature is not required (Figure 6).
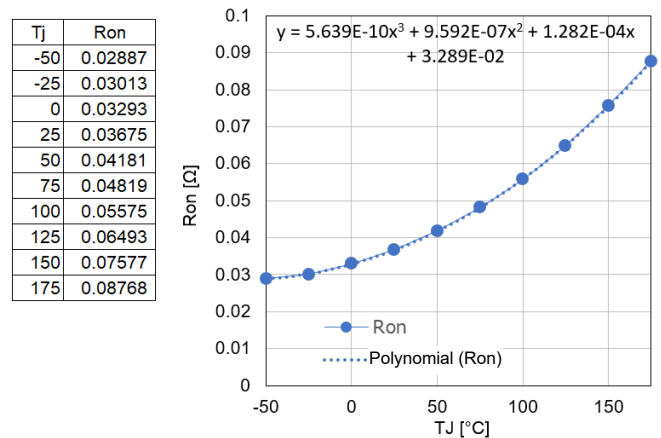
Tj	Ron
-50	0.02887
-25	0.03013
0	0.03293
25	0.03675
50	0.04181
75	0.04819
100	0.05575
125	0.06493
150	0.07577
175	0.08768

$y = 5.639E{-}10x^3 + 9.592E{-}07x^2 + 1.282E{-}04x + 3.289E{-}02$

Figure 4. Using Excel to create a graph from the read values, and displaying a trendline and the approximation equation

Gate threshold voltage	V$_{GS (th)}$	V$_{DS}$ = 10V, I$_D$ = 11.1mA	2.6	-	4.6	V
Static Drain - Source on - state resistance	R$_{DS(on)}$ *8	V$_{GS}$ = 18V, I$_D$ = 21A				
		T$_{vj}$ = 25°C	-	36	47	mΩ
		T$_{vj}$ = 150°C	-	72	-	
Gate input resistance	R$_g$	f = 1MHz, open drain		1		Ω

Figure 5. Standard value of the on-resistance in the data sheet

x	y	y×1.3056
Tj	Ron typ	Ron max
70	0.04676	0.06105
71	0.04703	0.06140
72	0.04730	0.06176
73	0.04758	0.06212
74	0.04786	0.06248
172	0.08619	0.11253
173	0.08670	0.11319
174	0.08721	0.11386
175	0.08772	0.11453

Figure 6. Using the approximation equation to calculate the maximum value of the on-resistance at each temperature

Next, calculate the power consumption at each temperature. Use Equation 2 for calculating the power consumption. Use the value calculated from Figure 6 for the on-resistance at each temperature (Figure 7).

Tj	Ron	P_D
70	0.06104	17.64
71	0.06140	17.74
72	0.06176	17.85
73	0.06212	17.95
74	0.06248	18.06
≈		≈
172	0.11252	32.52
173	0.11319	32.71
174	0.11386	32.90
175	0.11453	33.10

Figure 7. Using Equation 2 to calculate the power consumption at each temperature

Next, calculate the heat dissipation curve of the case. The heat dissipation power of the case (P_C) can be calculated with Equation 3.

$$P_C = \frac{T_J - T_A}{R_{thJC} + R_{thCH} + R_{thHA}} \quad [W] \tag{3}$$

T_J: Junction temperature [°C]

T_A: Ambient temperature [°C]

R_{thJC}: Thermal resistance from the junction to the case [°C/W]

R_{thCH}: Thermal resistance from the case to the heat sink [°C/W]

R_{thHA}: Thermal resistance from the heat sink to the ambient temperature [°C/W]

Since the heat dissipation curve is linear, calculate the low and high temperature points only (Figure 8).

T_J	Pc = (T_J-T_A) / (R_{thJC}+R_{thCH}+R_{thHA})
70	1.67
175	36.67

Figure 8. Using Equation 3 to calculate the heat dissipation curve

Display power consumption P_D calculated above overlaid on heat dissipation power P_C in the graph (Figure 9). The junction temperature is the temperature at which power consumption (heat generation power) P_D is equal to heat dissipation power P_C ($P_D = P_C$). In the graph, the point of intersection of the two curves is the junction temperature. Enlarge the scale to read the temperature (Figure 10). In this example, the temperature is 151.2°C, exceeding the absolute maximum rating of the device.
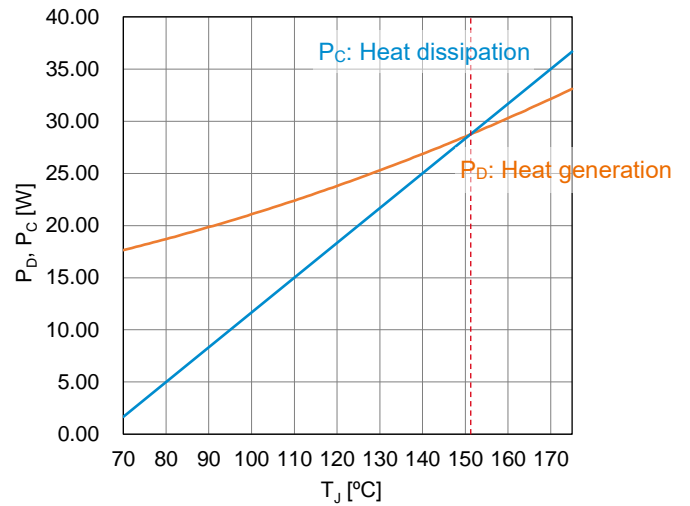

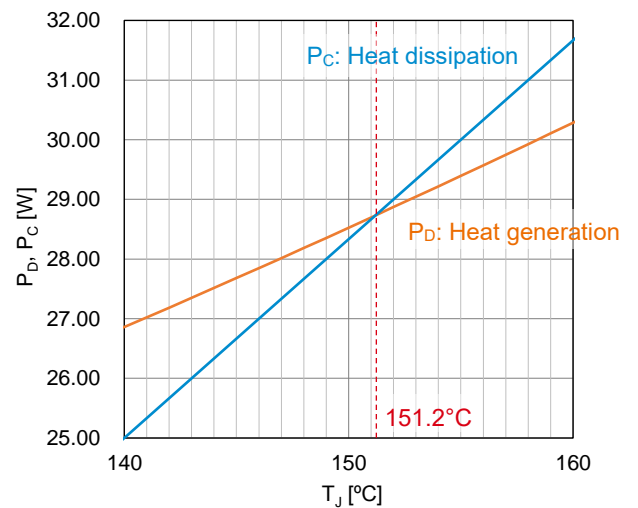Figure 9. Displaying power consumption P_D overlaid on heat dissipation power P_C

Figure 10. Enlarging the scale to read the temperature at the point of intersection

Now, calculate the junction temperature with Equations 1 and 2 using the maximum value of $R_{DS(on)}$ at 25°C (Figure 5) for the calculation of P_D.

$$P_D = I_D^2 \times R_{DS(on)} = 17^2 \times 47 \times 10^{-3} = 13.58 \ [W]$$

$$T_J = \left(R_{thJC} + R_{thCH} + R_{thHA}\right) \times P_D + T_A$$
$$= (0.85 + 0.67 + 1.48) \times 13.58 + 65 = 105.7 \ [°C]$$

The result is as much as 45.5°C lower than the correct calculation. Thus, the power consumption may be incorrectly estimated if the value at the practical (high) temperature is not used, causing a thermal problem in the actual equipment.

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