# Calculating the Temperature of Discrete Semiconductor Devices

## Description

This document describes how to calculate the temperature of discrete semiconductor devices.

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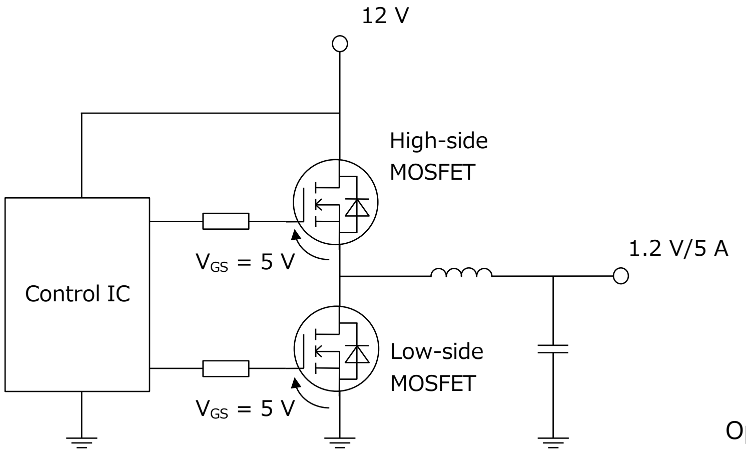
# 1. Introduction

Discrete semiconductor devices are used in various conditions and environments. In particular, power semiconductor devices handle high power. Because of the high power density, the generated heat could damage permanently or degrade the lifetime of power semiconductor devices. Temperature is therefore the most important parameter for power semiconductor devices. This document uses MOSFETs as an example to demonstrate how to calculate channel temperature using the measured waveform. This method can also be used to calculate the temperature of other types of semiconductor devices.

# 2. Acquiring operating waveforms

This document describes how to calculate the channel temperature of the high-side MOSFET of a buck converter shown in Figure 2.1, based on its operating waveform. First, in order to calculate its power dissipation, obtain the waveforms of its drain-source voltage $V_{DS}$ and drain current $I_D$ waveforms as shown in Figure 2.2 to Figure 2.5. At this time, adjust the time axis of the oscilloscope display to observe the MOSFET waveform for one to two cycles. In addition, obtain an enlarged view of the drain current as shown in Figure 2.3 in order to calculate the conduction losses of the MOSFET. For the calculation of the switching loss, acquire enlarged views of the period during which switching losses occur ( i.e., the period during which the $V_{DS}$ and $I_D$ waveforms cross ) as shown in Figure 2.4 and Figure 2.5. Also measure the ambient temperature $T_a$.




Operating conditions:

- $V_{IN}$ = 12 V
- $V_{OUT}$ ≈ 1.2 V
- $I_{OUT}$ ≈ 5 A
- $V_{GS}$ = 5 V
- $f_{SW}$ = 315 kHz
- $T_a$ = 50°C

**Figure 2.1 Example of a buck converter**

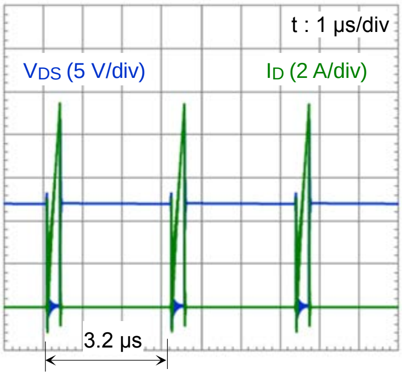



Figure 2.2 Overall switching waveform (Waveform #1)

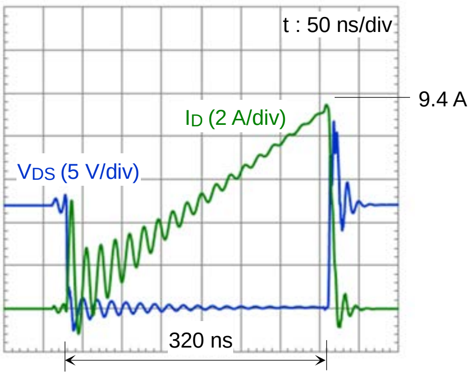



Figure 2.3 Drain current waveform (Waveform #2)

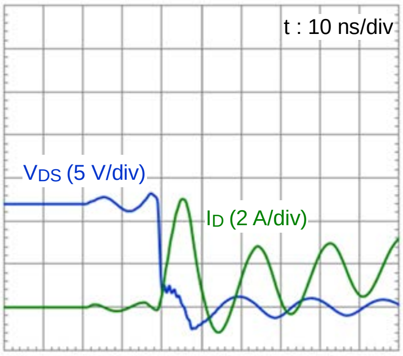



Figure 2.4 Turn-on waveform (Waveform #3)

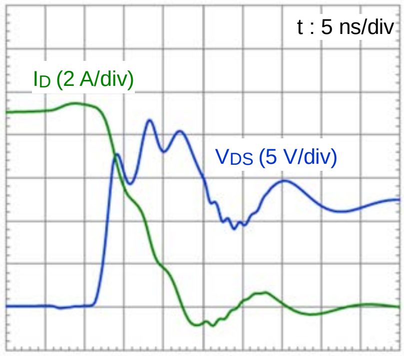



Figure 2.5 Turn-off waveform (Waveform #4)

* All waveforms presented herein, including those shown above, are intended merely to indicate a typical operation of a MOSFET.

# 3. Calculating the channel temperature of a MOSFET operating at a fixed duty cycle

## 3.1. Calculating channel temperature

When a repetitive pulse train with a cycle period of T is applied as shown in Figure 3.1, $T_{ch\ (max)}$ in a thermally stable state is calculated using Equation 3-1:

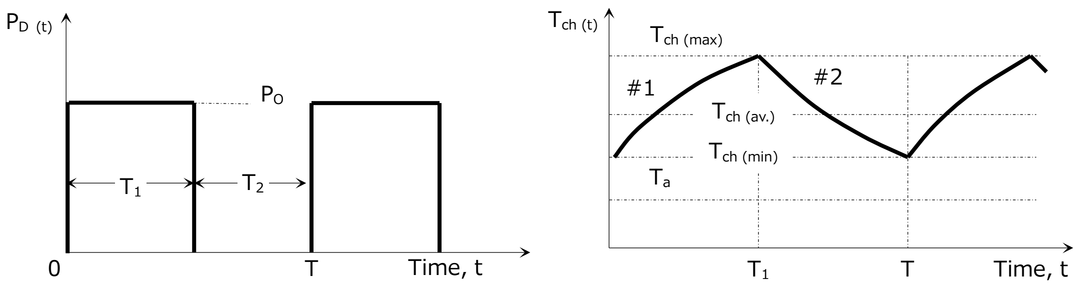



Figure 3.1 Changes in temperature caused by the application of a pulsed waveform

$$T_{ch\,(max)} = P_O \cdot \left[\frac{T_1}{T} \cdot R_{th(ch-a)} + \left(1 - \frac{T_1}{T}\right) \cdot r_{th}(T + T_1) - r_{th}(T) + r_{th}(T_1)\right] + T_a \quad \cdots (\ 3\text{-}1\ )$$

However, the power dissipation waveform rarely becomes a clean rectangular wave. To calculate $T_{ch\ (max)}$, use Equation 3-1 to approximate the power dissipation waveform to a rectangular shape as shown in Figure 3.2.

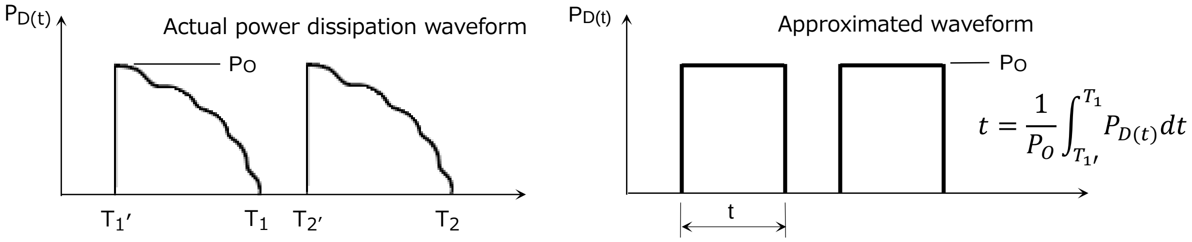



**Figure 3.2 Approximation of a power dissipation waveform**

In order to accurately transform a waveform into a rectangular shape, it is necessary to perform integral approximation. If the power dissipation $P_D$ waveform is rectangular or triangular, $P_D$ can be approximated as shown in Figure 3.3.

( a ) and ( b ) show a rectangle having the same area as a sine wave or a triangular wave. In ( a ) and ( b ), the rectangle has a height of $0.7P_D$ and a width of 0.91t or 0.71t.

In ( c ) and ( d ), the peak power dissipation remains unchanged before and after conversion; in this case, the rectangles with the same area as a sine or triangular wave have a width of 0.63t and t/2 respectively.

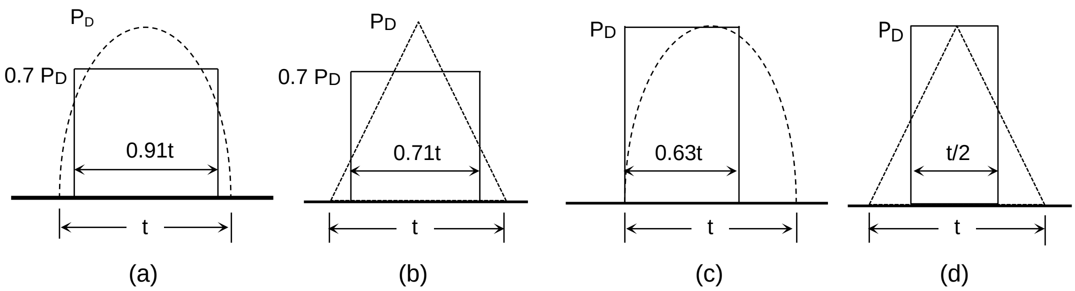



**Figure 3.3 Waveform approximation**

## 3.2. Calculating a rise in temperature during a conduction period

### 3.2.1. Calculating on-resistance

On-resistance has a positive temperature coefficient. Calculate the maximum on-resistance at a channel temperature $T_{ch}$ of 150°C ( i.e., absolute maximum temperature ) using on-resistance data shown in a datasheet.

$$R_{DS(ON)\,(max)} = R_{DS(ON)max}@25^\circ\mathrm{C} \cdot \frac{R_{DS(ON)typ.}@150^\circ\mathrm{C}}{R_{DS(ON)typ.}@25^\circ\mathrm{C}} \cdot Margin \quad \cdots (\ 3\text{-}2\ )$$

Table 3.1, Figure 3.4 and Figure 3.5 are excerpts from a datasheet of a high-side MOSFET. Read an on-resistance at 150°C and substitute it into Equation 3-2. The circuit shown in Figure 2.1 operates at a $V_{GS}$ of 5 V. Figure 2.3 shows that the peak drain current of the MOSFET is 9.4 A. From the $V_{DS}$ - $V_{GS}$ curve of Figure 3.4, the $R_{DS(ON)}$ value at 5 V is approximately 1 mΩ lower than that at 4.5 V. From the $V_{GS}$ = 4.5V/ $I_D$ = 10A curve, read the $R_{DS(ON)}$ value at 150°C and consider this difference in $R_{DS(ON)}$ at 4.5 V and 5 V. Equation 3-3 considers for a 10% margin for $R_{DS(ON)}$.

$$R_{DS(ON)max} = \left(0.016 \times \frac{0.018}{0.0126} - 0.001\right) \times 1.1$$
$$\approx 0.0240\ (\Omega) \qquad \cdots (3\text{-}3)$$

**Table 3.1 On-resistance characteristics of the high-side MOSFET**

( $T_a$=25°C )

| Characteristics | Symbol | Test Condition | Min | Typ. | Max | Unit |
|---|---|---|---|---|---|---|
| Drain-source on-resistance | $R_{DS(ON)}$ | $V_{GS}$ = 4.5 V, $I_D$ = 5 A | — | 12.6 | 16 | mΩ |
| | | $V_{GS}$ = 10 V, $I_D$ = 5.5 A | — | 9.4 | 11 | |

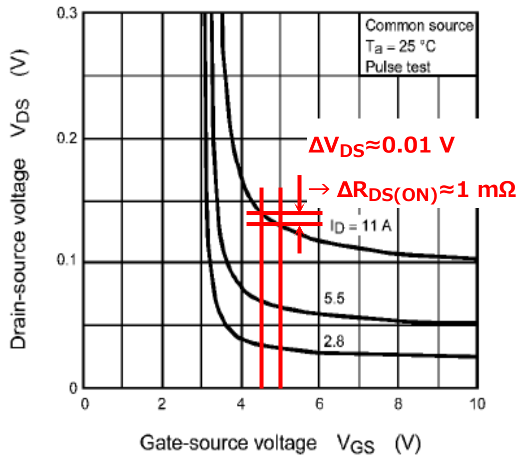



**Figure 3.4 $V_{DS}$ – $V_{GS}$ curves of the high-side MOSFET**

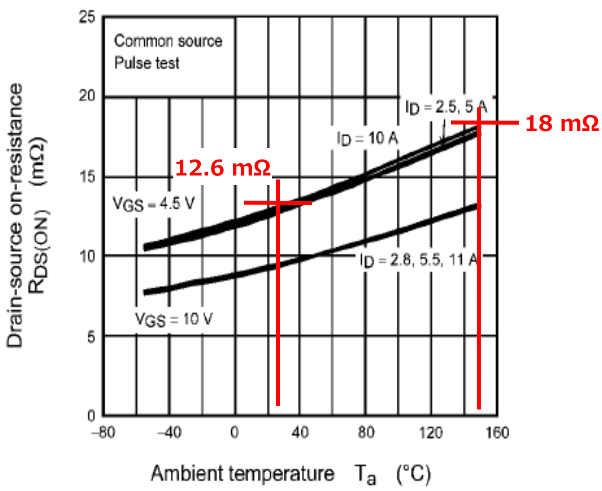



**Figure 3.5 $R_{DS(ON)}$ – Ta curves of the high-side MOSFET**

### 3.2.2. Calculating conduction losses

From the waveform of Figure 2.3 and the on-resistance calculated using Equation 3-3, the peak conduction loss can be calculated as follows using Equation 3-4.

$$\begin{aligned} P_{o\ peak} &= {I_D}^2 \cdot R_{DS(ON)\ (max)} \\ &= 9.4^2 \times 0.0240 \\ &\approx 2.12\ (W) \end{aligned} \quad \cdots\ (\ 3\text{-}4\ )$$

Suppose that the conduction loss waveform is triangular. Then, it can be approximated to a rectangle using the method shown in Figure 3.3( b ).

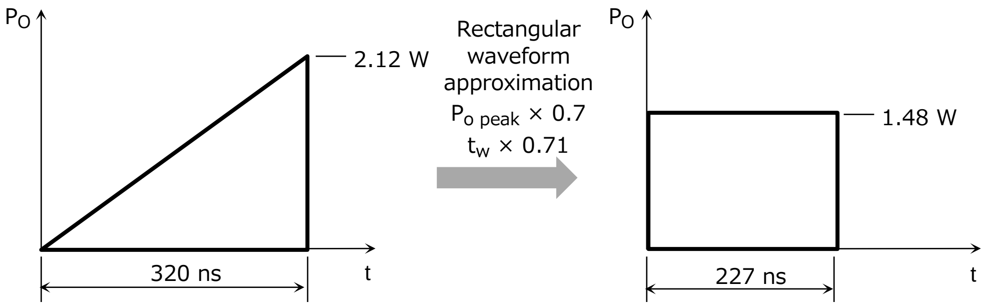



**Figure 3.6 Rectangular waveform approximation during a conduction loss period**

### 3.2.3. Calculating a rise in temperature caused by current conduction

Figure 3.7 is an excerpt of transient thermal impedance curves from the datasheet. Read thermal impedance values at the cycle period and the conduction loss period. Generally, for a pulse width less than 100 μs, the logarithmic curve is linearly extrapolated to obtain transient thermal impedance. Since the lowest pulse width on the horizontal axis is 100 μs in Figure 3-7, use Equation 3-5 for a narrower pulse:

$$r_{th}(t_{w1}) = r_{th}(t_{w2}) \cdot \sqrt{\frac{t_{w1}}{t_{w2}}} \quad \cdots\ (\ 3\text{-}5\ )$$

$t_{w1}$: Pulse width at which transient thermal impedance is to be calculated
$t_{w2}$: Minimum pulse width shown in the datasheet
$r_{th}(t_{w1})$: Transient thermal impedance at $t_{w1}$
$r_{th}(t_{w2})$: Transient thermal impedance at $t_{w2}$

Note: The symbol $Z_{th}$ is sometimes used to represent transient thermal impedance.

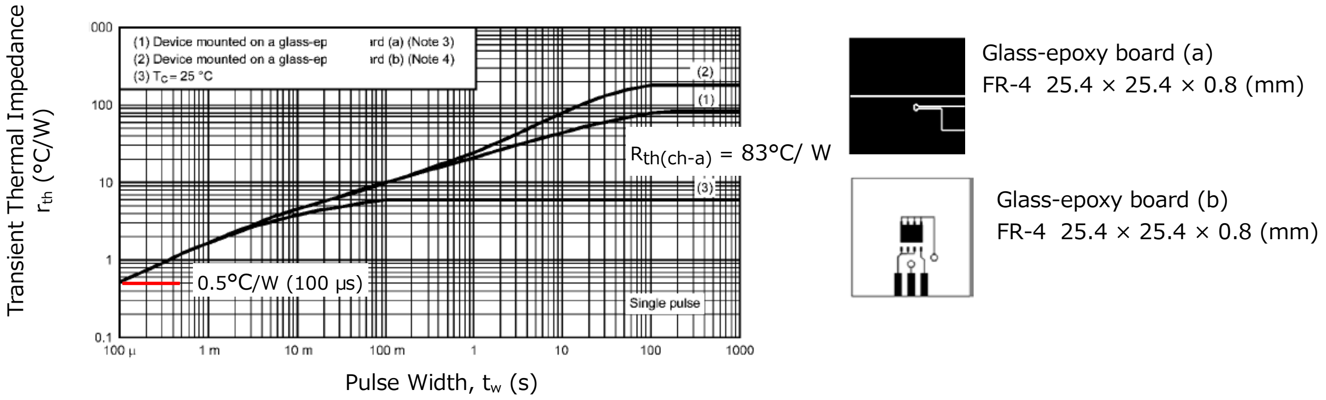



**Figure 3.7 Transient thermal impedance curves of the high-side MOSFET**

For a cycle period of 3.2 μs, transient thermal impedance is calculated as follows. Table 3.2 lists transient thermal impedance values that will be used to calculate a temperature rise during the conduction period approximated in Figure 3.6.

$$
\begin{aligned}
r_{th}(3.2\mu s) &= r_{th}(100\mu s) \cdot \sqrt{\frac{3.2 \times 10^{-6}}{100 \times 10^{-6}}} \\
&= 0.5 \times \sqrt{\frac{3.2 \times 10^{-6}}{100 \times 10^{-6}}} \\
&\approx 0.089\ (℃/W) \qquad \cdots (\text{3-6})
\end{aligned}
$$

**Table 3.2 Transient thermal impedances during conduction**

| | Pulse width | Transient thermal impedance (°C/W) |
|---|---|---|
| $r_{th}$ (100 μs) | 100 μs | 0.5 |
| $r_{th}(T)$ | 3.2 μs | 0.089 |
| $r_{th}(T_1)$ | 227ns | 0.024 |
| $r_{th}(T+T_1)$ | 3.427 μs | 0.093 |

Here, suppose that the MOSFET is mounted on a glass-epoxy board ( a ) shown in Figure 3.7. Then, substituting these values into Equation 3-1, a rise in channel temperature during conduction is calculated as shown below.

$$
\begin{aligned}
\Delta T_{ch(cond.)} &= P_{o_{peak}} \cdot \left[\frac{T_1}{T} \cdot R_{th(ch-a)} + \left(1 - \frac{T_1}{T}\right) \cdot r_{th}(T + T_1) - r_{th}(T) + r_{th}(T_1)\right] \\
&= 1.48 \times \left[\frac{227 \times 10^{-9}}{3.2 \times 10^{-6}} \times 83 + \left(1 - \frac{227 \times 10^{-9}}{3.2 \times 10^{-6}}\right) \times 0.093 - 0.089 + 0.024\right] \\
&\approx 8.7\ (℃) \qquad \cdots (\text{3-7})
\end{aligned}
$$

### 3.3. Calculating a rise in temperature during turn-on

In Figure 3.8, the yellow areas surrounded by the intersections of the $V_{DS}$ and $I_D$ curves represent turn-on losses. Use graph-to-data converter software or data acquisition software available with an oscilloscope to convert these areas into a turn-on loss waveform like the one shown in Figure 3.9.

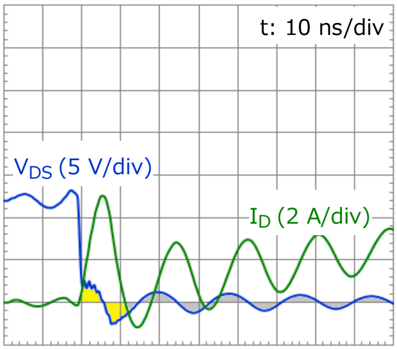



Figure 3.8 Turn-on waveform

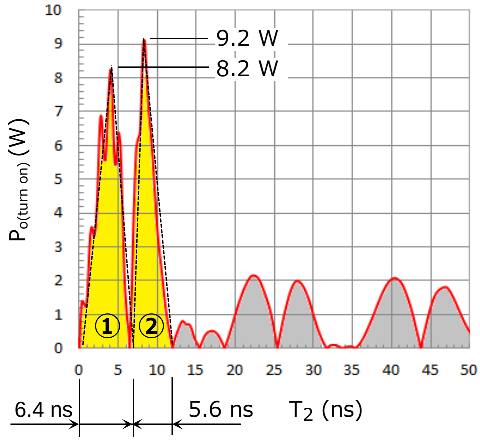



Figure 3.9 Turn-on loss waveform

※ Losses also occur in gray areas, but they are ignored here since they are smaller than the yellow areas.

Approximate the triangles ① and ② as rectangles in order to calculate transient thermal impedances during respective periods. Then, use Equation 3-8 and 3-9 to calculate the resulting rise in temperature during turn-on.

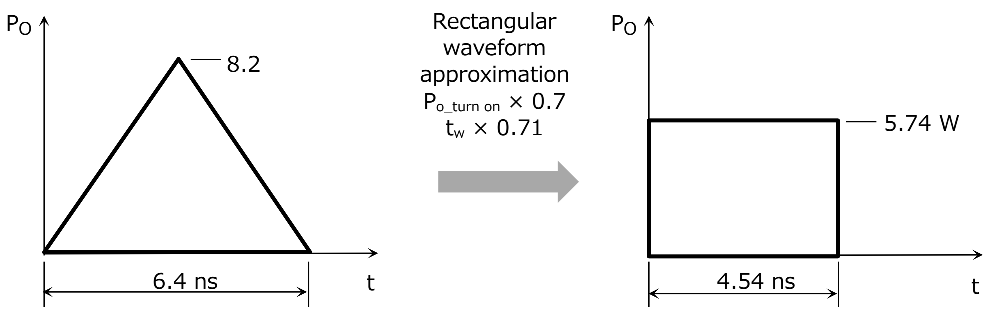



**Figure 3.10 Rectangular waveform approximation during turn-off period ①**

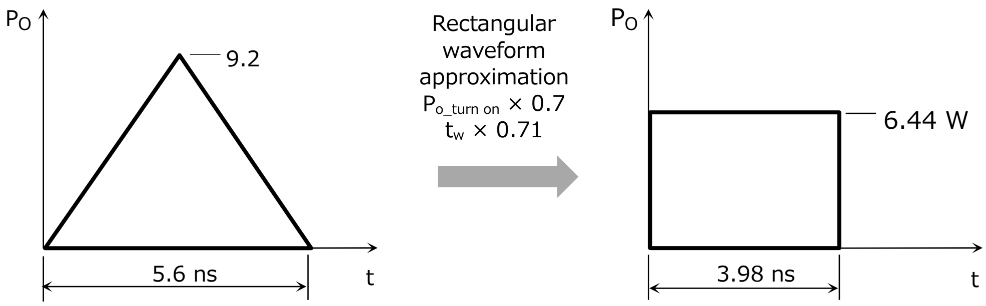



**Figure 3.11 Rectangular waveform approximation during turn-off period ②**

**Table 3.3 Transient thermal impedances during turn-on**

| | | Pulse width | Transient thermal impedance (°C/W) |
|---|---|---|---|
| ① | $r_{th}(T)$ | 3.2 μs | 0.089 |
| | $r_{th}(T_2')$ | 4.54 ns | 0.003 |
| | $r_{th}(T+T_2')$ | 3.204 μs | 0.090 |
| ② | $r_{th}(T)$ | 3.2 μs | 0.089 |
| | $r_{th}(T_2'')$ | 3.98 ns | 0.003 |
| | $r_{th}(T+T_2'')$ | 3.204 μs | 0.089 |

$$\Delta T_{ch(turn\,on①)} = P_{o_{(turn\,on①)}} \cdot \left[\frac{T_2'}{T} \cdot R_{th(ch-a)} + \left(1 - \frac{T_2'}{T}\right) \cdot r_{th}(T + T_2') - r_{th}(T) + r_{th}(T_2')\right]$$
$$= 5.74 \times \left[\frac{4.54 \times 10^{-9}}{3.2 \times 10^{-6}} \times 83 + \left(1 - \frac{4.54 \times 10^{-9}}{3.2 \times 10^{-6}}\right) \times 0.090 - 0.089 + 0.003\right]$$
$$\approx 0.7\ (°C) \qquad \cdots (3\text{-}8)$$

$$\Delta T_{ch(turn\,on②)} = P_{o_{(turn\,on②)}} \cdot \left[\frac{T_2''}{T} \cdot R_{th(ch-a)} + \left(1 - \frac{T_2''}{T}\right) \cdot r_{th}(T + T_2'') - r_{th}(T) + r_{th}(T_2'')\right]$$
$$= 6.44 \times \left[\frac{3.98 \times 10^{-9}}{3.2 \times 10^{-6}} \times 83 + \left(1 - \frac{3.98 \times 10^{-9}}{3.2 \times 10^{-6}}\right) \times 0.089 - 0.089 + 0.003\right]$$
$$\approx 0.7\ (°C) \qquad \cdots (3\text{-}9)$$

## 3.4. Calculating a rise in temperature during turn-off

As is the case with a temperature rise during turn-on, obtain a turn-off loss waveform like the one shown in Figure 3.13 from the $V_{DS}$ and $I_D$ waveforms of Figure 3.12. Approximate the triangular area to a rectangle and calculate transient thermal impedances for each pulse width. Then, calculate the resulting rise in temperature.

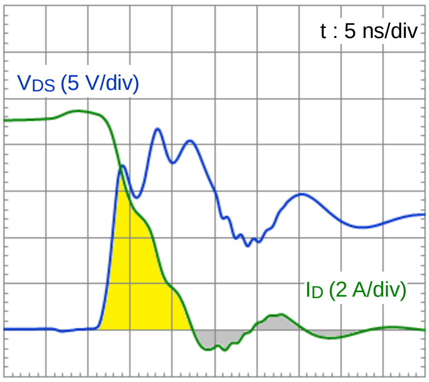



**Figure 3.12 Turn-off waveform**

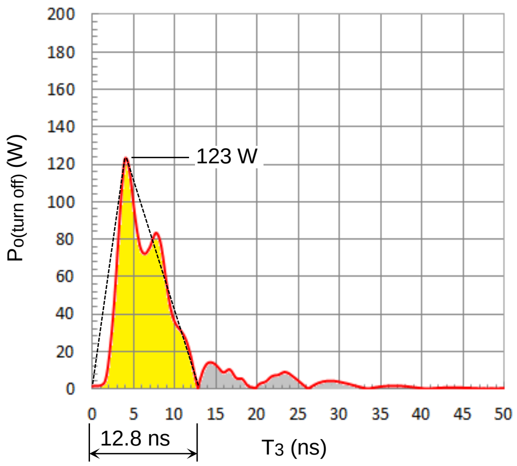



**Figure 3.13 Turn-off loss waveform**

※ Losses also occur in gray areas, but they are ignored here since they are smaller than the yellow area.

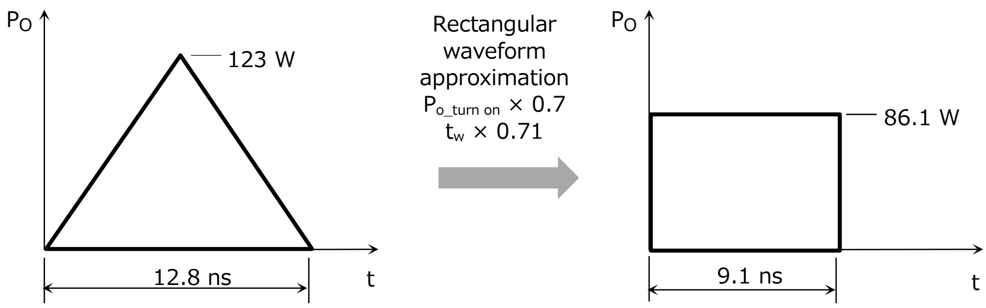



**Figure 3.14 Rectangular waveform approximation during a turn-off period**

**Table 3.4 Transient thermal impedances during turn-off**

| | Pulse width | Transient thermal impedance (°C/W) |
|---|---|---|
| $r_{th}$ (100 μs) | 100 μs | 0.5 |
| $r_{th}(T)$ | 3.2 μs | 0.089 |
| $r_{th}(T_3)$ | 9.1 ns | 0.005 |
| $r_{th}(T+T_3)$ | 3.209 μs | 0.090 |

$$\begin{aligned}\Delta T_{ch(turn\,off)} &= P_{O(turn\,off)} \cdot \left[\frac{T_3}{T} \cdot R_{th(ch-a)} + \left(1 - \frac{T_3}{T}\right) \cdot r_{th}(T+T_3) - r_{th}(T) + r_{th}(T_3)\right] \\ &= 86.1 \times \left[\frac{9.1 \times 10^{-9}}{3.2 \times 10^{-6}} \times 83 + \left(1 - \frac{9.1 \times 10^{-9}}{3.2 \times 10^{-9}}\right) \times 0.090 - 0.089 + 0.005\right] \\ &\approx 20.7\ (°\mathrm{C})\end{aligned} \qquad \cdots (3\text{-}10)$$

## 3.5. Calculating the maximum channel temperature

Suppose that the high-side MOSFET operates as shown in Figure 2.2 ( Waveform #1 ). Then, use Equation 3-11 to calculate the maximum channel temperature, which adds the sum of the temperature rises calculated thus far to the ambient temperature.

$$\begin{aligned}T_{ch\,(max)} &= \Delta T_{ch(cond.)} + \Delta T_{ch(turn\,on①)} + \Delta T_{ch(turn\,on②)} + \Delta T_{ch(turn\,off)} + Ta \\ &= 8.7 + 0.7 + 0.7 + 20.7 + 50 \\ &\approx 80.8\ (°\mathrm{C})\end{aligned} \qquad \cdots (3\text{-}11)$$

This result confirms that the maximum channel temperature will not exceed the rated maximum temperature of 150°C. When calculating channel temperature, you need to evaluate the possible worst-case conditions in a real application and ensure that the MOSFET has not only a sufficient temperature margin but also margins for all the other ratings.

Suppose, for example, that the case temperature is known for a MOSFET in a through-hole package ( e.g., TO-220 ) with a heatsink. Then, you can calculate the peak channel temperature in the same manner by replacing $R_{th(ch\text{-}a)}$ and $T_a$ in Equation 3-1 with $R_{th(ch\text{-}c)}$ and $T_c$, respectively.

# 4. Calculating the channel temperature in the case of an intermittent, repetitive loss waveform

An intermittent, repetitive loss waveform like the one shown in Figure 4.1 can be transformed as shown in Figure 4.2. Therefore, the channel temperature can be calculated using Equation 4-1.

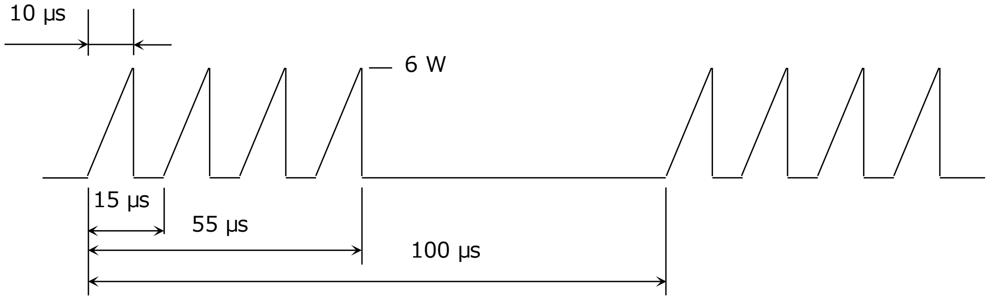
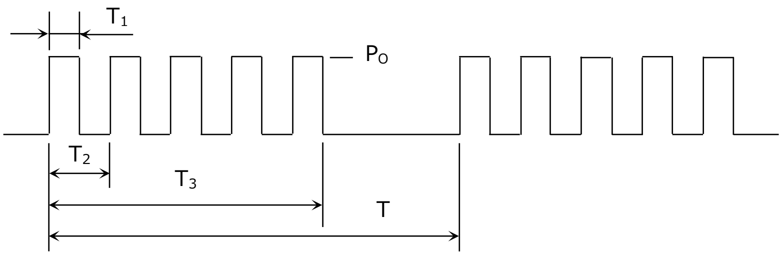



**Figure 4.1 Intermittent, repetitive loss waveform**



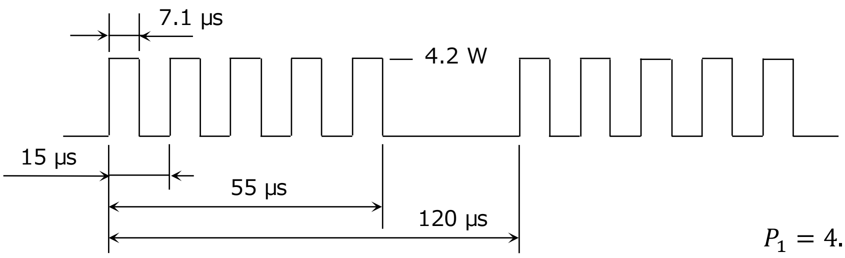

$$P_1 = P_O \cdot \frac{T_1}{T_2}$$

$$P_2 = P_1 \cdot \frac{T_3}{T}$$

**Figure 4.2 Transformation of an intermittent, repetitive loss waveform**

$$T_{ch(\max)} = P_2 \cdot \left[R_{th(ch-a)} - r_{th}(T_3)\right] + P_1 \cdot [r_{th}(T_3) - r_{th}(T_1 + T_2)] + P_O \cdot [r_{th}(T_1 + T_2) - r_{th}(T_2) + r_{th}(T_1)] + Ta \quad \cdots (4\text{-}1)$$

Approximate the loss waveform of Figure 4.1 to a rectangular waveform as shown in Figure 4.3. Suppose $R_{th(ch-a)}$ = 83°C/W and $T_a$ = 50°C. Use these values and the transient thermal impedance curves of Figure 3.7 to calculate channel temperature.




$$P_1 = 4.2 \times \frac{7.1 \times 10^{-6}}{15 \times 10^{-6}} \approx 1.99\ (W)$$

$$P_2 = 1.99 \times \frac{55 \times 10^{-6}}{100 \times 10^{-6}} \approx 1.09\ (W)$$

**Figure 4.3 Loss waveform approximated to a rectangular waveform**

$$T_{ch(\max)} = 1.09 \times (83 - 0.371) + 1.99 \times (0.371 - 0.235) + 4.2 \times (0.235 - 0.194 + 0.133) + 50 \approx 141.1\ (°C) \quad \cdots (4\text{-}2)$$

**Table 4.1 Transient thermal impedances in each period**

| | Pulse width | Transient thermal impedance (°C/W) |
|---|---|---|
| $r_{th}(T_1)$ | 7.1 μs | 0.133 |
| $r_{th}(T_2)$ | 15 μs | 0.194 |
| $r_{th}(T_1+T_2)$ | 22.1 μs | 0.235 |
| $r_{th}(T_3)$ | 55 μs | 0.371 |

This result confirms that the loss waveform shown in Figure 4.1 does not cause the peak channel temperature, $T_{ch(max)}$, to exceed 150°C. However, the channel temperature does not have a sufficient margin relative to the maximum channel temperature rating of the MOSFET. It is therefore necessary to reconsider thermal dissipation conditions or select another MOSFET.

## 5. Obtaining operating waveforms

Care should be exercised in using a voltage probe, a current probe or a current-sense transformer to obtain a device's operating waveforms.

### 5.1. Using a voltage probe

To measure a voltage with a voltage probe, the attached GND lead is generally used as shown in Figure 5.1. Since the GND lead has a large parasitic inductance, a MOSFET that operates at a high frequency may exhibit ringing. The GND lead may also work as an antenna, causing the MOSFET to be affected by noise. A voltage across two terminals of a device should be measured with the minimum length of the GND lead. The voltage can be measured accurately by connecting a probe, with a hook tip removed, to a board connector. It is also possible to measure a voltage by wrapping a plated wire around the probe head with the hook tip removed as shown in Figure 5.2.

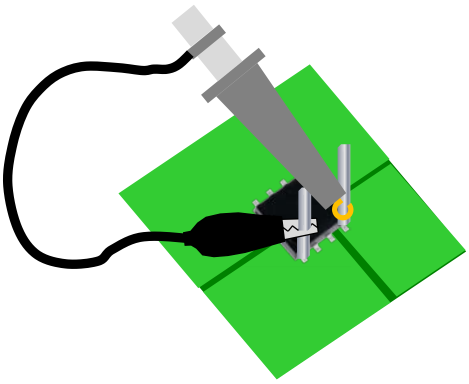


**Figure 5.1 Voltage measurement using the GND lead of a voltage probe**

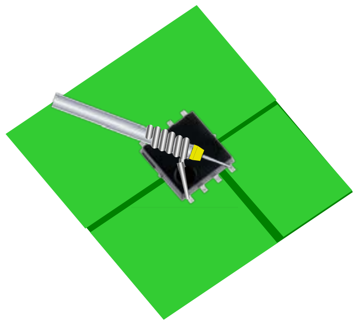


**Figure 5.2 Minimizing the length of the GND lead for voltage measurement**

## 5.2. Using a current probe and a current-sense transformer

To measure a current of the circuit shown in Figure 5.3 using a current probe or a current-sense transformer, part of the board trace is cut in order to connect a lead for current sensing. Care should be exercised as to the position to which the lead is connected. Figure 5.4 to Figure 5.9 show the drain-source voltage $V_{DS}$ and drain current $I_D$ waveforms. To obtain these waveforms, we connected a lead with a diameter of 2 mm and a length of roughly 60 mm to either the drain or source terminal of the MOSFET. When the lead was connected to the drain, the measured waveforms were almost identical to those obtained without using a lead. However, when the lead was connected to the source, accurate waveforms could not be obtained; the $V_{DS}$ and $I_D$ waveforms were delayed due to the effect of the lead inductances. It is therefore necessary to connect a current-sense lead to the drain in order to obtain accurate current waveforms.

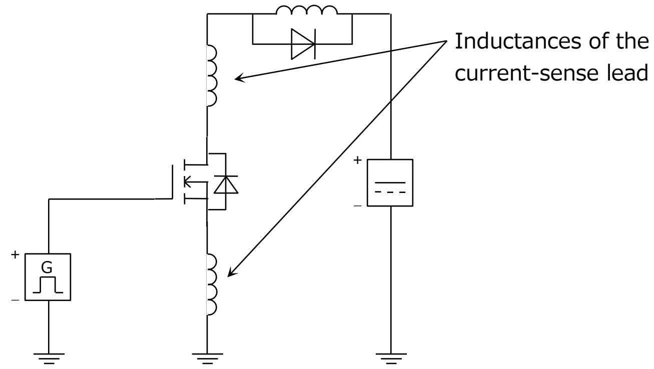



**Figure 5.3 Circuit with an inductive load**

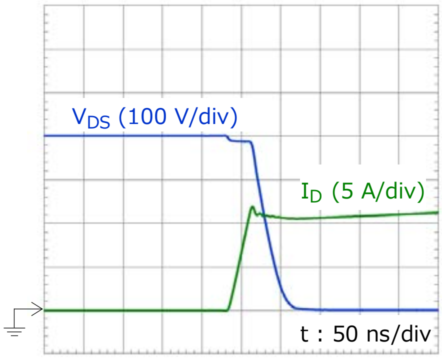



**Figure 5.4 Turn-on waveform**
**( Without a current-sense lead )**

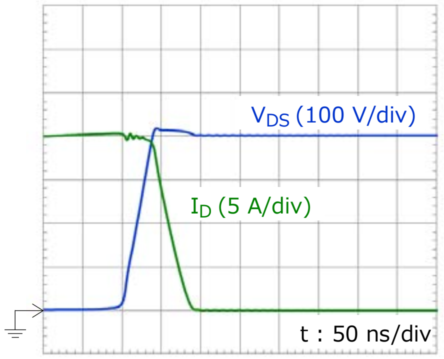



**Figure 5.5 Turn-off waveform**
**( Without a current-sense lead )**

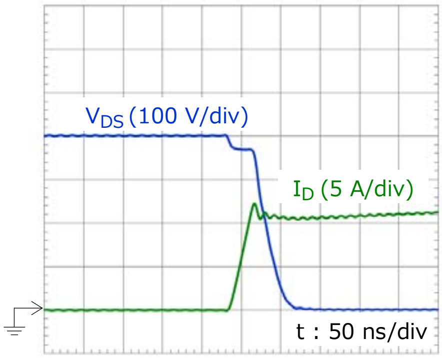



**Figure 5.6 Turn-on waveform**
**( A current-sense lead is connected to the drain )**

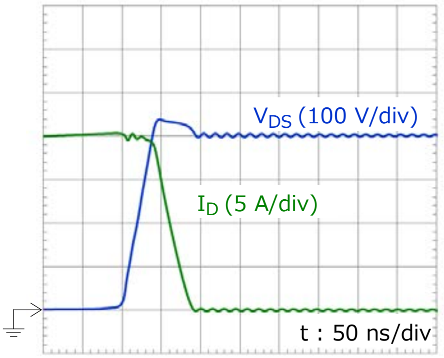



**Figure 5.7 Turn-off waveform**
**( A current-sense lead is connected to the drain)**

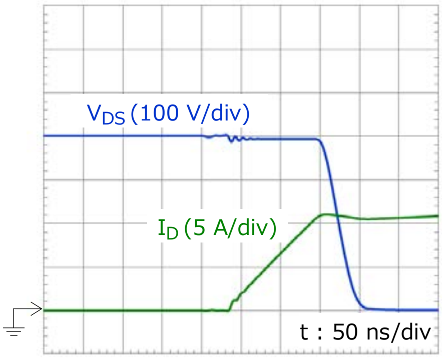



**Figure 5.8 Turn-on waveform**
**( A current-sense lead is connected to the source )**

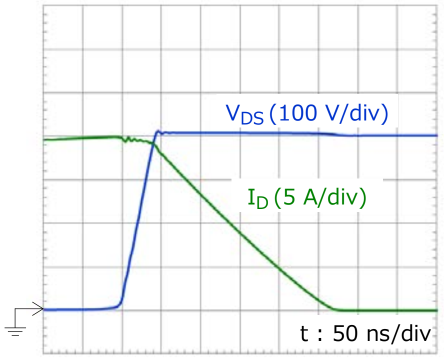



**Figure 5.9 Turn-off waveform**
**( A current-sense lead is connected to the source)**

## 6. Supplemental explanation

Equation 3-1 is derived from the waveforms shown in Figure 6.1. When a loss $P_O$ occurs repetitively at a fixed interval as shown in ( a ), the average loss throughout the entire period is first calculated. Then, a rise in channel temperature is calculated, assuming the application of loss pulses for two cycles. ( b ) shows an approximation of ( a ). ( c ) is a different representation of ( b ) using the principle of superposition. Add the changes in loss $P_O$-$P_{av}$ caused by the loss pulses during the period from $T_4$ to $T_5$. Since no loss occurs during the period from $T_5$ to $T_6$, subtract $P_O$ from the total of $T_4$–$T_5$. Since $P_O$ is applied again during the period from $T_6$ to $T_7$, add $P_O$ to obtain a rise in temperature at $T_7$. You can find the peak channel temperature by adding this result to the ambient temperature.

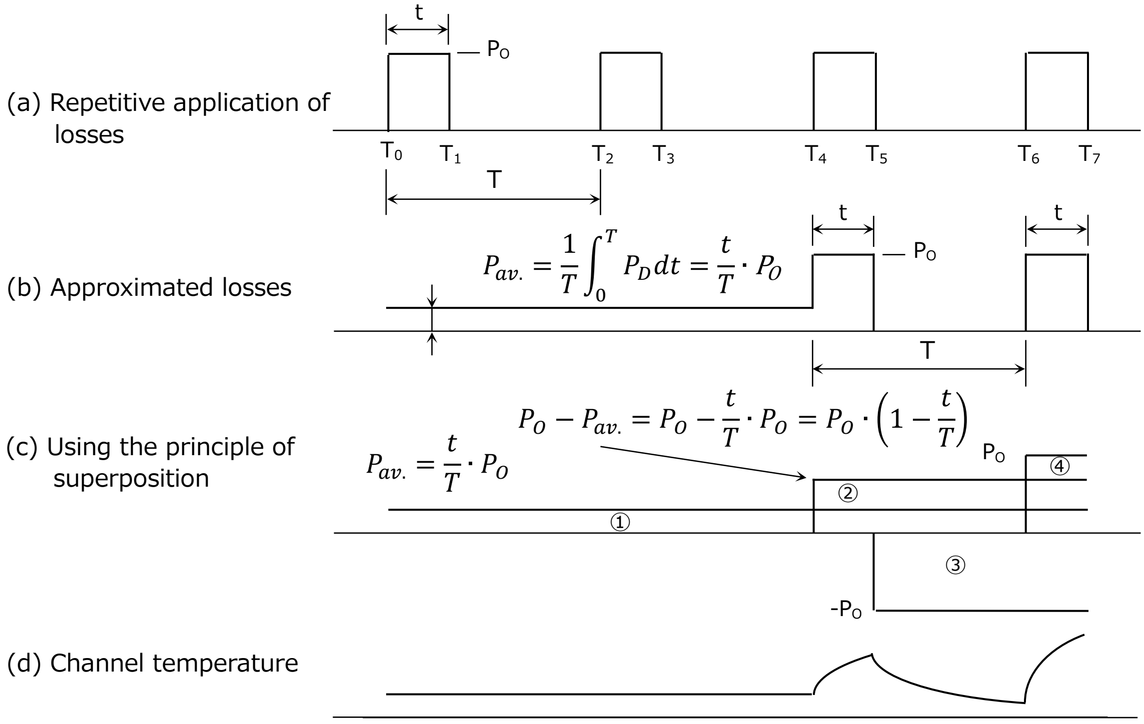



**Figure 6.1 Rise in channel temperature caused by a repetitive waveform**

The temperature rises caused by ① to ④ in ( c ) can be calculated using Equation 6-1 to Equation 6-4.

$$\Delta T_{ch①} = P_O \cdot \frac{t}{T} \cdot R_{th(ch-a)} \qquad \cdots (6\text{-}1)$$

$$\Delta T_{ch②} = P_O \cdot \left(1 - \frac{t}{T}\right) \cdot r_{th}(T + t) \qquad \cdots (6\text{-}2)$$

$$\Delta T_{ch③} = -P_O \cdot r_{th}(T) \qquad \cdots (6\text{-}3)$$

$$\Delta T_{ch④} = P_O \cdot r_{th}(t) \qquad \cdots (6\text{-}4)$$

Hence, the total channel temperature rise is expressed as Equation 6-5. The peak channel temperature ( Equation 3-1 ) is obtained by adding $\Delta T_{ch}$ to the ambient temperature $T_a$.

$$\Delta T_{ch} = P_O \cdot \frac{t}{T} \cdot R_{th(ch-a)} + P_O \cdot \left(1 - \frac{t}{T}\right) \cdot r_{th}(T+t) - P_O \cdot r_{th}(T) + P_O \cdot r_{th}(t)$$

$$= \mathrm{P}_O \cdot \left[\frac{t}{T} \cdot R_{th(ch-a)} + \left(1 - \frac{t}{T}\right) \cdot r_{th}(T+t) - r_{th}(T) + r_{th}(t)\right] \qquad \cdots (\ 6\text{-}5\ )$$

$$T_{ch\,(max)} = \mathrm{P}_O \cdot \left[\frac{t}{T} \cdot R_{th(ch-a)} + \left(1 - \frac{t}{T}\right) \cdot r_{th}(T+t) - r_{th}(T) + r_{th}(t)\right] + \mathrm{Ta} \qquad \cdots (\ 6\text{-}6\ )\ [*(\ 3\text{-}1\ )]$$

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