APPLICATION NOTE

GaN Device Channel Temperature, Thermal Resistance, and Reliability Estimates

Introduction

This application note explains how Qorvo calculates junction-to-case thermal resistance, or Θ_{JC}, for product datasheets and also provides a method for estimating device life given the expected device maximum operating temperature.

Referenced Documents

JESD51-1, "Integrated Circuit Thermal Measurement Method - Electrical Test Method (Single Semiconductor Device)"

JESD51-14, "Transient Dual Interface Test Method for the Measurement of the Thermal Resistance Junction-to-Case of Semiconductor Devices with Heat Flow Through a Single Path"

"GaN Thermal Analysis for High-Performance Systems," Qorvo White Paper
https://www.qorvo.com/resources/d/qorvo-gan-thermal-analysis-for-high-performance-systems-white-paper

"High Performance GaN Thermal Evaluation - Limitations of Infrared Microscopy," Qorvo White Paper
https://www.qorvo.com/resources/d/qorvo-high-performance-gan-thermal-evaluation-infrared-microscopy-limitations

"Understanding GaN Thermal Analysis," Qorvo® Instructional Video for more Qorvo GaN thermal analysis information
https://www.qorvo.com/design-hub/videos/understanding-gan-thermal-analysis

Determining Maximum Channel Temperature

Maximum Channel Temperature, $T_{CH,\,MAX}$

The most popular means to determine the maximum channel temperature of a GaN device under operation (assuming the die is viewable) is to use an infrared optical imaging system. IR cameras are a common and readily-accessible technology; they are relatively easy to operate and can provide quick results The limitations of IR cameras are: (1) reduced precision (an IR camera averages the temperature reading over its optical spot size); (2) difficulty imaging reflective surfaces (one remedy is to cover the imaged area with a low emissivity material, such as matte-black spray-paint); (3) it does not allow looking at the actual surface of the semiconductor material when covered by metal structures (e.g., air bridges).

Despite these limitations, IR remains a popular approach for many users of GaN devices. Accordingly, the industry generally reports $T_{CH,MAX}$ and Θ_{JC} data based off IR temperature measurements. Qorvo datasheets similarly list $T_{CH,MAX}$ and Θ_{JC} correlated with IR measurements. Doing so enables (1) direct application of customers' system-level IR measurement data, and (2) direct comparison with the thermal data listed on competitors' datasheets. The channel temperatures reported on Qorvo datasheets correspond to a 5 µm x 5 µm IR camera spot size.

Thermal Resistance, Θ_{JC}

JESD51-1 provides a standardized definition of junction-to-case thermal resistance (Θ_{JC}):

> The junction-to-case thermal resistance θ_{JC} is a measure of the ability of a semiconductor device to dissipate heat from the surface of the die to a heat sunk package surface. In JESD51-1 [N3] it has been defined as "the thermal resistance from the operating portion of a semiconductor device to the outside surface of the package (case) closest to the chip mounting area when that same surface is properly heat sunk so as to minimize temperature variation across that surface".
>
> The traditional thermocouple measurement as outlined in MIL standard 833 [N1] requires the determination of the junction temperature T_J, the case temperature T_C, and the heating power dissipation P_H, while the device is properly heat-sunk at the case. The junction-to-case thermal resistance is then calculated using
>
> $$\theta_{JC} = \frac{T_J - T_C}{P_H} \qquad (1)$$
>
> **(Excerpt taken from JESD51-14)**

Following JESD 51-1, the junction-to-case thermal resistance assumes the case temperature T_C is a fixed temperature on the package backside (usually 85 °C for GaN products). This is admittedly an idealized boundary condition, as it assumes the package is mounted on a perfect heat sink. For GaN die, the maximum temperature of the hottest channel (usually at the middle of a FET unit cell) is referred to as the junction temperature, i.e.,

$$T_{CH,MAX} = T_J$$

P_H in the formula for Θ_{JC} is the peak dissipated power in the given operating condition (not the time-averaged power). Thus, the value of $T_{CH,MAX}$ is dependent on the specific operating condition and will change with the pulse width and duty cycle. $T_{CH,MAX}$ is highest at CW operation after the system has achieved thermal steady-state operation.

In Figure 1, $T_{CH,MAX}$ is plotted against time for a packaged GaN device operated at a duty cycle of 10% and a pulse width of 100 µs, while the backside of the package is held at a fixed temperature of 85 °C. $T_{CH,MAX}$ reaches a peak value of ~150 °C near the end of the pulse.

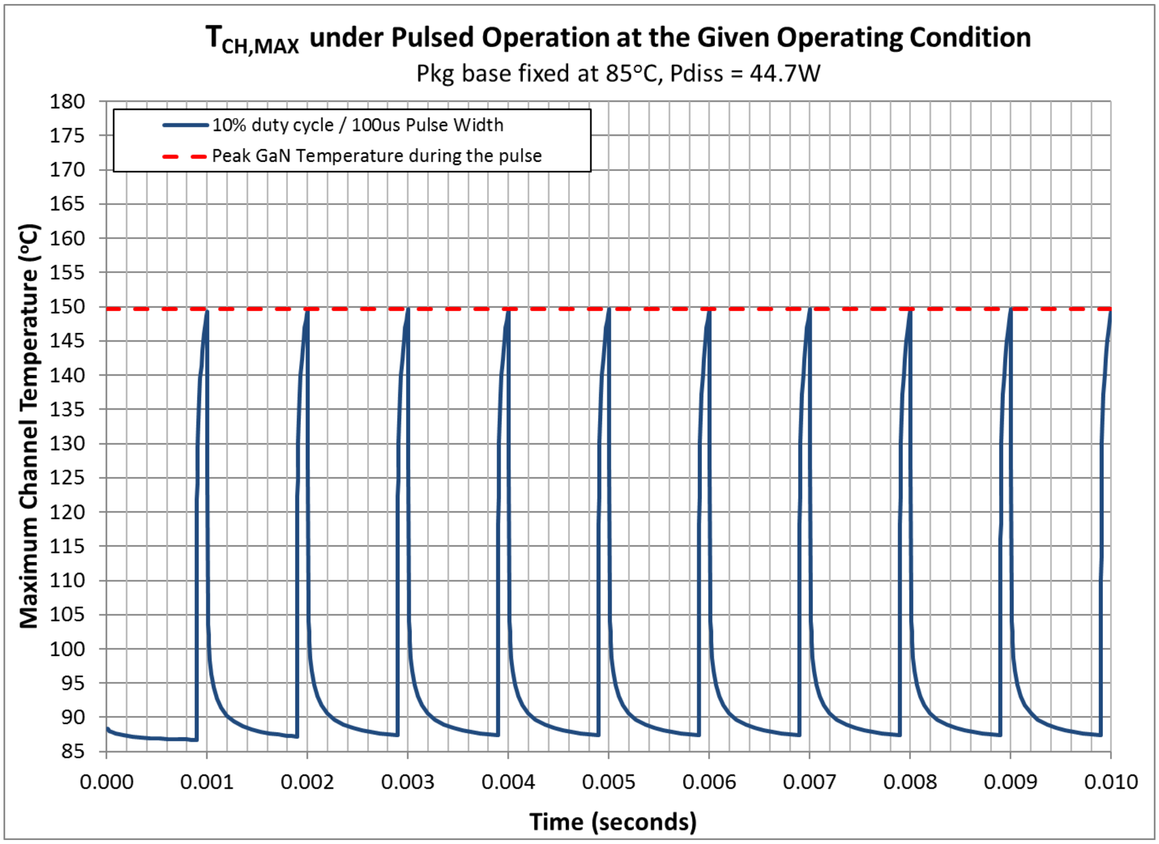


Figure 1. Response of $T_{CH,MAX}$ under Pulsed Operation

Using the above formula for Θ_{JC}:

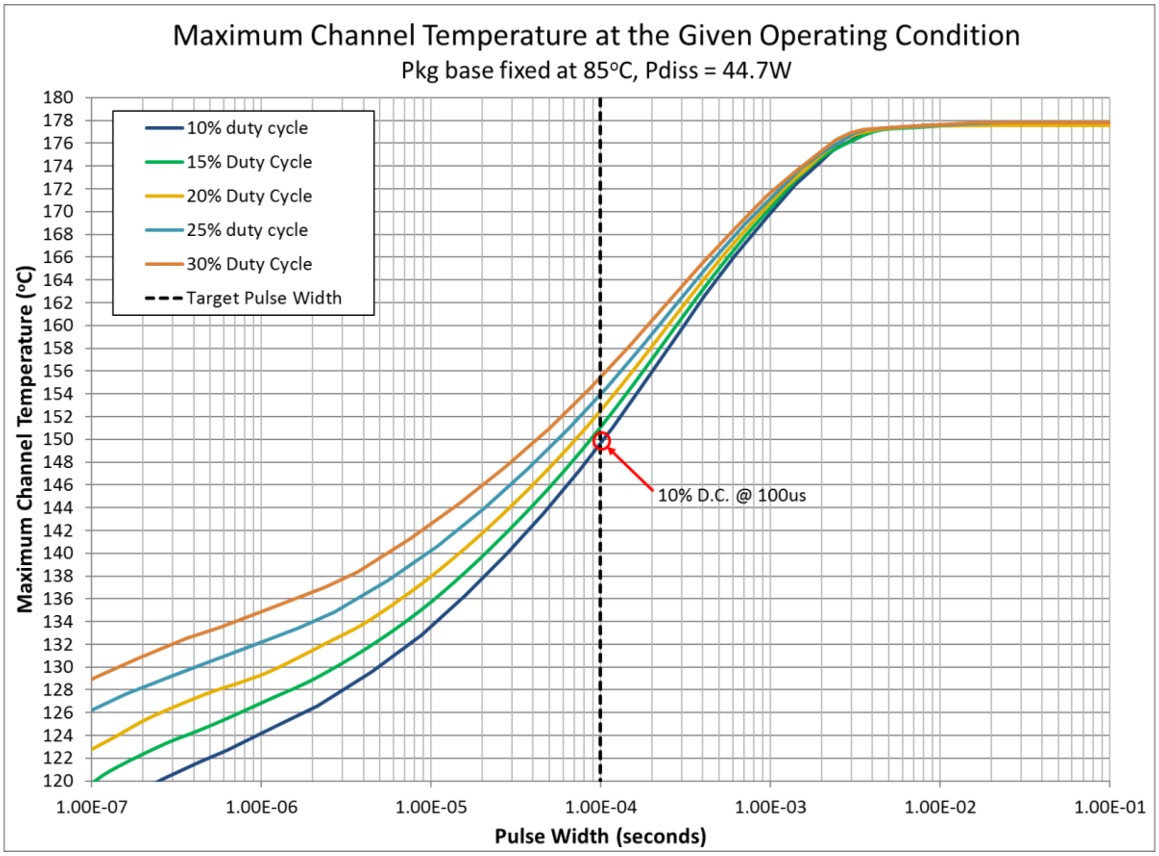
$$T_J = T_{CH,MAX} = 150\ °C$$

$$T_C = 85\ °C$$

$$P_H = P_{DISS} = 44.7\ W$$

$$\Theta_{JC} = (150\ °C - 85\ °C) / 44.7\ W = 1.45\ °C/W$$

The pulse width sensitivity plot of Figure 2 illustrates how $T_{CH,MAX}$ (and consequently Θ_{JC}) is a function of duty cycle and pulse width:



Peak Channel Temperature and θ_{JC} Calculation					
Pkg Backside Fixed Temp.	Duty Cycle/ Pulse width	$T_{CH,MAX}$	Pulsed P_{DISS}	Time-Averaged P_{DISS}	$\Theta_{JC} = (T_{CH,MAX} - T_C) / (\text{Pulsed } P_{DISS})$
C	% /usec	C	W	W	C/W
85	10% / 100	150.0	44.7	4.47	1.45
85	15% / 100	151.0	44.7	6.71	1.48
85	20% / 100	153.0	44.7	8.94	1.52
85	25% / 100	154.0	44.7	11.18	1.54
85	30% / 100	155.0	44.7	13.41	1.57
85	CW	177.8	44.7	44.70	2.08

Figure 2. $T_{CH,MAX}$ and Θ_{JC} for Various Operating Conditions

The selection of the case temperature Tc also impacts Θ_{JC}. The thermal conductivity of most semiconductor materials varies with temperature, decreasing as the material gets hotter. This dependence on temperature is illustrated in Figure 3 for Gallium Nitride (GaN) and Figure 4 for Silicon Carbide (SiC):

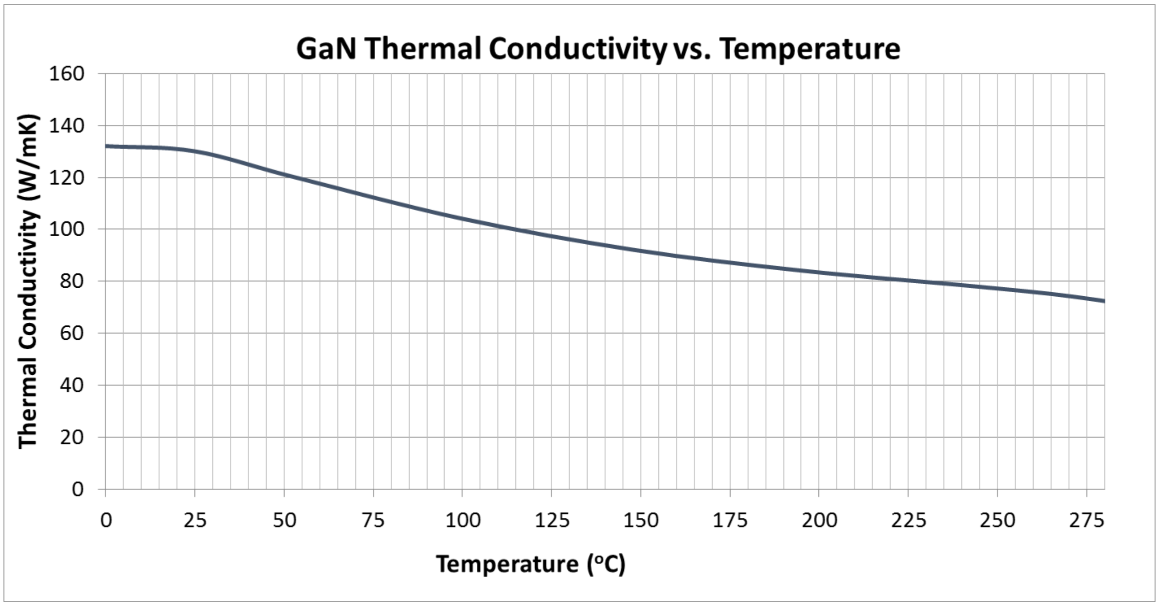


Figure 3. Thermal Conductivity of GaN

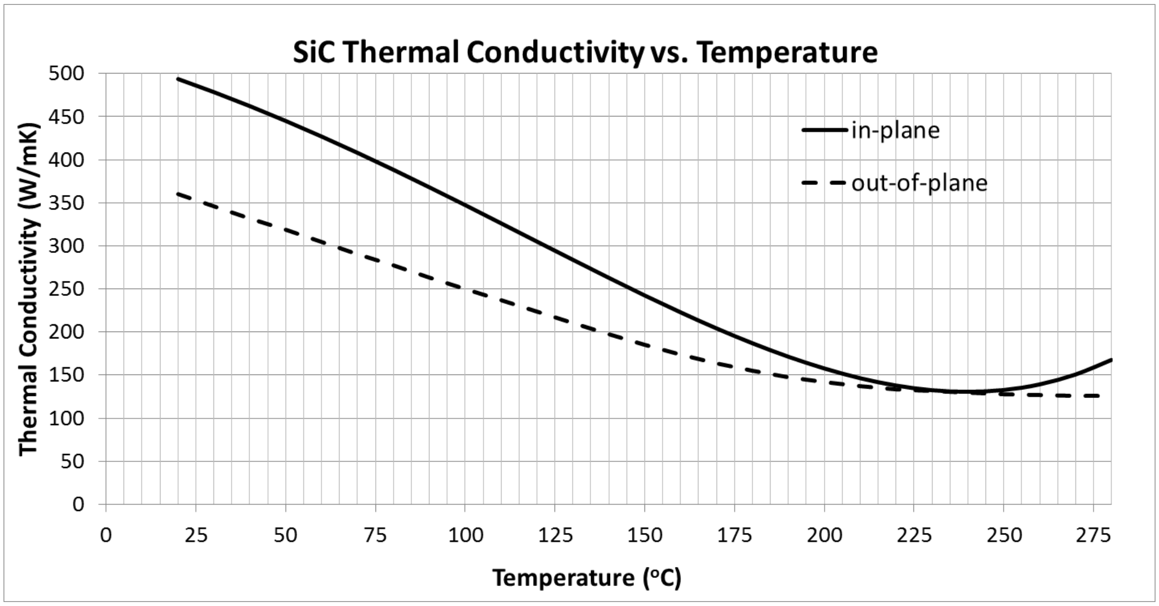


Figure 4. Thermal Conductivity of SiC

The temperature-dependent thermal conductivity impacts the accuracy of the standardized JESD51-1 formula for Θ_{JC}, since the material can dissipate heat more effectively at lower temperatures. For example, if P_{DISS} is held constant, but T_C is lowered to 65 °C from 85 °C (a decrease of 20 °C), $T_{CH,MAX}$ will drop by more than 20 °C. As a result, Θ_{JC} will slightly decrease.

Estimating Device Life

While Qorvo's product datasheets maximize the utility of IR temperature data, Qorvo's device reliability estimates are based on thermal simulations, verified by micro-Raman[1] measurements. This approach provides more accurate temperature estimates; whereas IR measurements will generally underestimate maximum temperatures, micro-Raman thermography enables precise sub-surface temperature measurement near the gate area with sub-micron resolution. The main drawbacks of micro-Raman thermography are the higher expense and the additional time and expertise required to perform the measurements.

Finite element models, which have been correlated with the micro-Raman data, are used to determine the power and environmental conditions required to run devices at specific elevated temperatures for accelerated life testing under DC power. The resulting measured device lifetime data is used for construction of a reliability Arrhenius plot which is applicable to all devices built with that process technology; this plot is commonly referred to as the median-time-to-failure curve. Figure 5 shows the curves for Qorvo's GaN25, GaN25-HV, and GaN15 process technologies.

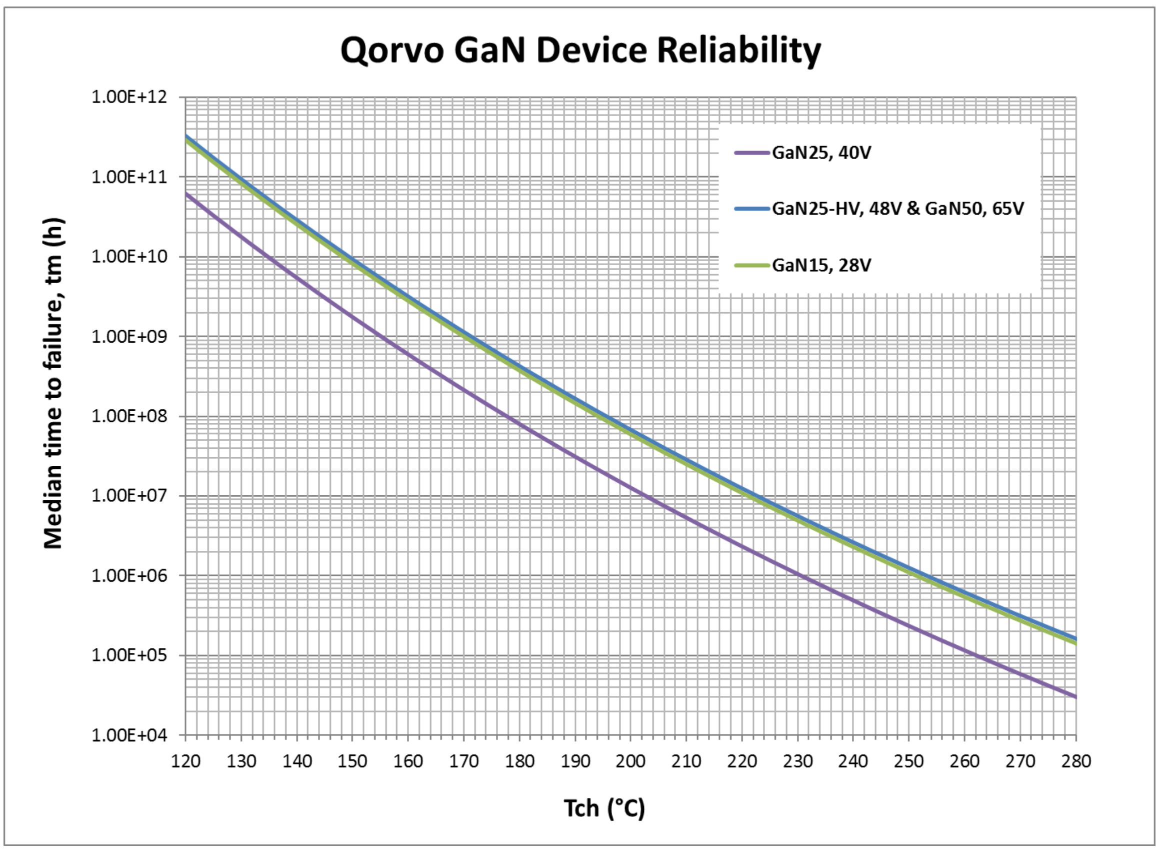


Figure 5. Median Time To Failure for Qorvo's GaN devices; curves are based on 3 – temperature DC life test data, where the targeted T_{CH} values are determined by micro-Raman correlated FEA simulation.

[1] Micro-Raman thermography is a precision technique for measuring temperatures at a sub-micron scale; it provides better estimates of device maximum temperature than conventional infrared (IR) thermography. For a more detailed explanation, and a discussion on limitations of IR Microscopy, please see the Qorvo white paper *High Performance GaN Thermal Evaluation - Limitations of Infrared Microscopy*

Since the curves of Figure 5 are based on correlated finite element models, the modeled maximum GaN channel temperature (i.e., not an IR-measured value) must be used with those curves to predict device life in an application. IR measurements must be translated to FEA-modeled T_{CH} results to obtain device life estimates from the Arrhenius plot. The chart in Figure 6 provides the finite element model estimate of $T_{CH,MAX}$ corresponding to the IR-estimate of $T_{CH,MAX}$ for a given package backside temperature (T_C).

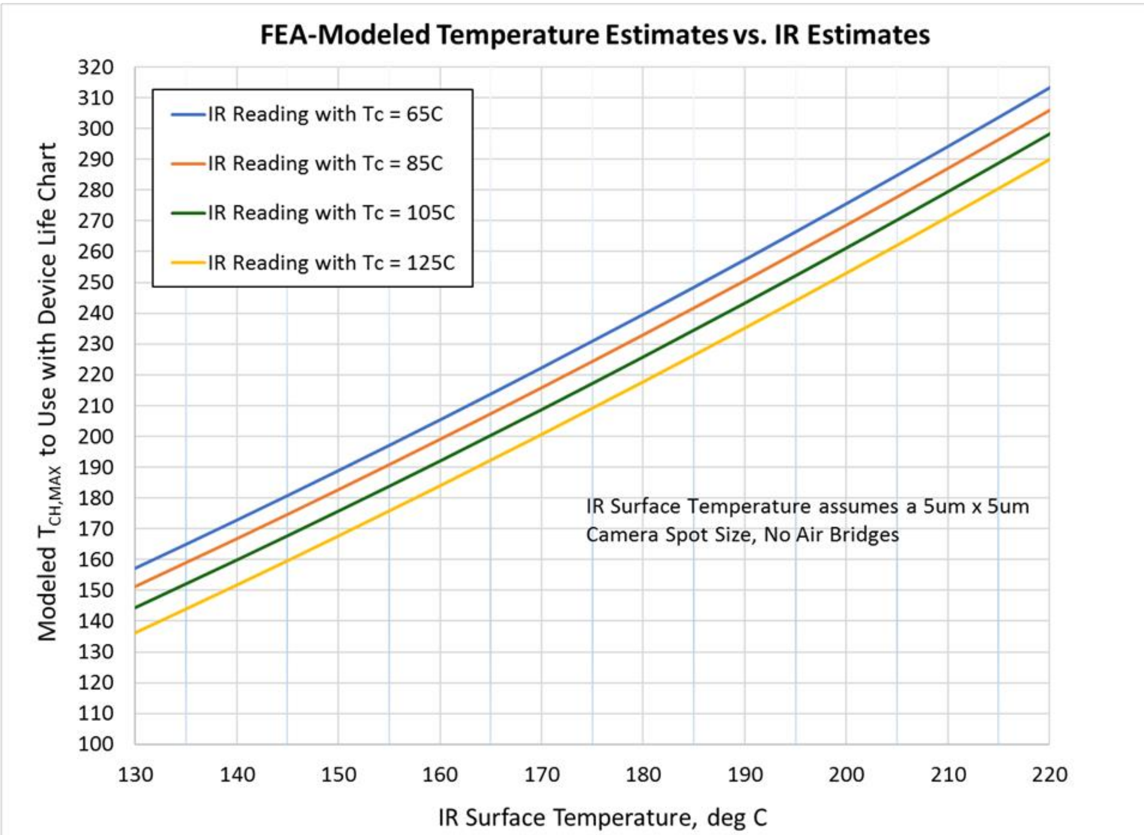


Figure 6. Adjusting IR-based $T_{CH,MAX}$ Estimates for use with Device Life Chart

Lastly, the Arrhenius plots of Figure 5 assume CW operation (i.e., $T_{CH,MAX}$ is held at steady-state). In the case of pulsed operation at typical duty cycles and pulse widths, the peak value of $T_{CH,MAX}$ is held for only a few microseconds. Figure 7 shows a zoomed-in view of the 100 µs pulse width, 10% duty cycle $T_{CH,MAX}$ thermal waveform shown in Figure 1.

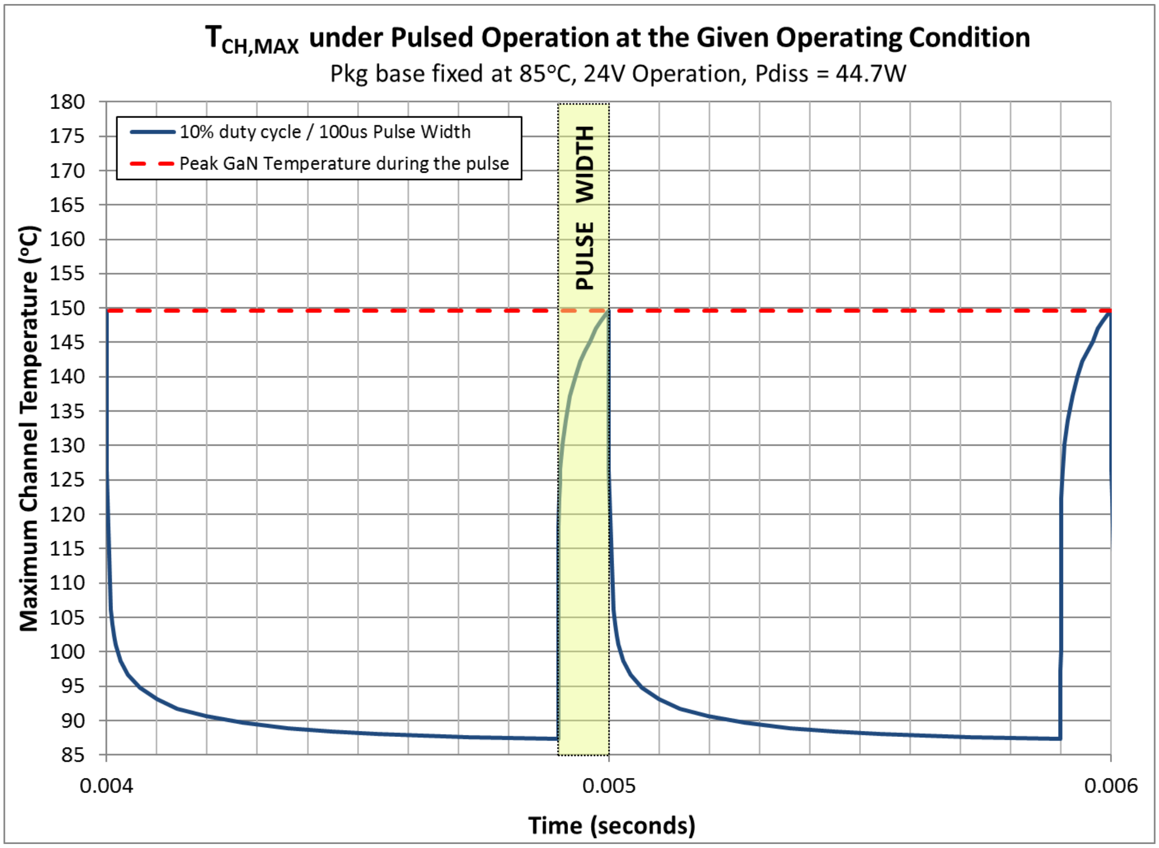


Figure 7. Zoom-in of Figure 1 to Show Response of $T_{CH,MAX}$ During the Pulse Width

As the graph shows, $T_{CH,MAX}$ exists at the peak value of ~150 °C for a much shorter duration than the pulse width. A simple approach to approximating device life is to assume that $T_{CH,MAX}$ = 150 °C for the entire 100 µs pulse and to further assume that all device fatigue occurs during the 100 µs pulse. Given these assumptions, the device life for this pulsed operating condition can be estimated by dividing the predicted life by the 10% duty cycle (i.e., life is 10× the chart prediction).

In summary, to obtain an estimate of device life:

1. Adjust the IR-based GaN surface temperature (the value on the Qorvo datasheet) to an equivalent FE model-based temperature using Figure 6.
2. Read the estimated device operating life from Figure 5.
3. If not operating at CW, convert operating life to a pulsed approximation by dividing the estimated device operating life by the duty cycle (e.g., life is 10× for 10%, 5× for 20%, or 2× for 50%, when compared to CW).

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