Understanding Datasheet Thermal Parameters and IC Junction Temperatures

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Introduction

There is much confusion regarding how to make meaningful design decisions when converting a datasheet's thermal resistance parameters.

This introductory webinar will help today's hardware engineers understand the thermal parameters found in datasheets — including whether to choose theta vs. psi, how to calculate these values, and, most importantly, how to apply these values to a design in a practical manner.

This webinar will also describe the relationship between application ambient temperatures, as well as how they compare to PCB temperatures or IC junction temperatures.

Lastly, it will discuss how power dissipation changes with temperature, and how to use this characteristic to achieve a cool-running, cost-optimized solution.

Electrothermal Analogy

Certain analogies can be made between thermal and electrical quantities. Table 1 and 2 compare electrical and thermal quantities, as well as their material constants.

Table 1: Analog Relationships between Electrical and Thermal Quantities (1)

Electrical Quantities (1)			Thermal Quantities (2)		
Quantity	Formula Symbol	Unit	Quantity	Formula Symbol	Unit
Voltage	$U(t)$	V	Temperature difference	$\Delta T(t)$	K
Current	$I(t) = \frac{dQ_{el}}{dt}$	A	Heat flow	$\Phi(t) = \frac{dQ_{th}}{dt}$	W
Charge	$Q_{el}(t) = \int I\, dt$	$A \times s$	Heat quantity	$Q_{th}(t) = \int \Phi\, dt$	$W \times s$
Capacitance	C_{el}	$\frac{A \times s}{V}$	Heat capacity	$C_{th} = c \times \rho \times V$	$\frac{W \times s}{K}$
Resistance	$R_{el} = \frac{L}{\varkappa \times A}$	$\Omega = \frac{V}{A}$	Thermal resistance	$R_{th} = \frac{L}{\lambda \times A}$	$\frac{K}{W}$
Conductance	$Gel = \frac{I}{Rel}$	$S = \frac{A}{V}$	Thermal conductivity	$G_{th} = \frac{I}{Rth}$	$\frac{W}{K}$
Electric Conductivity	$\varkappa$	$\frac{A}{V \times m}$	Thermal conductivity	λ	$\frac{W}{m \times K}$

Note:

1) The contents of this table are from *Technische Temperaturmessung: Volume I*, Frank Bernhard, ISBN 978-3-642-62344-8.
2) el refers to electrical values, and th refers to thermal values.

Electrothermal Analogy

Table 2: Material Constants and Variables for Different Materials

Formula Symbol	Quantity	Descriptions and Examples	Values	Units
ρ (Greek rho)	Density	Volumetric mass density of a substance		$\frac{kg}{m^3}$
λ (Greek lambda)	Thermal conductivity	Thermal conductivity of a material, ability to conduct heat		$\frac{W}{m \times K}$
		Copper	388	
		Aluminum	205	
		Silicon	180	
		Solder SAC405 (16% of Cu)	62	
		Ceramic BaTio3 (MLCCs)	2.9	
		Die attach epoxy	2.4	
		Mold compound	1	
		FR4, in-plane ↔	0.8 to 1	
		FR4, through-plane ↕	0.2 to 0.4	
		Air	0.026	
ϰ (Greek kappa)	Electric conductivity	Material's ability to allow the transport of an electric charge		$\frac{1}{\Omega \times m}$
		Copper	58.6×10^{-6}	
		Aluminum	37.7×10^{-6}	
		Solder (13% of Cu)	7.6×10^{-6}	

Electrothermal Analogy

Table 2 (continued): Material Constants and Variables for Different Materials

Formula Symbol	Quantity	Descriptions and Examples	Values	Units
c	Specific heat capacity	Amount of heat required to raise the temperature of 1kg of a substance by 1K		$\frac{Ws}{kg \times K}$
		Water	4179.6	
		FR4	1300	
		Aluminium	900	
		Copper	389	
L	Length	1-dimensional object size		m
A	Area	2-dimensional extend of a shape		m^2
V	Volume	3-dimensional space enclosed by a boundary		m^3
θ_{JA} (Greek theta)	Thermal resistance	Junction-to-air thermal resistance for a defined PCB		$\frac{K}{W}$
θ_{JC} (Greek theta)	Thermal resistance	Junction-to-case thermal resistance for a defined PCB		$\frac{K}{W}$
Ψ_{JT} or Ψ_{JB} (Greek psi)	Thermal resistance characteristics	Junction-to-case (top) or to-board thermal resistance. Characterized parameter based on a measurement		$\frac{K}{W}$

Equations for Electrical and Thermal Analogy

Electrical and thermal quantities can be calculated in networks, and are comparable to Kirchhoff's rules (see Table 3).

Table 3: Analogy between the Equations of Electrical and Thermal Processes [3]

Basic Electrical Equations	Basic Thermal Equations
Series connection of electrical resistors: $R_{el} = R1_{el} + R2_{el} + \ldots + Rnel$	Series connection of thermal resistors: $R_{th} = R1_{th} + R2_{th} + \ldots + Rnth$
Parallel connection of electrical resistors: $\frac{I}{R_{el}} = \frac{I}{R1_{el}} + \frac{I}{R2_{el}} + \ldots + \frac{I}{Rn_{el}}$	Parallel connection of thermal resistors: $\frac{I}{R_{th}} = \frac{I}{R1_{th}} + \frac{I}{R2_{th}} + \ldots + \frac{I}{Rn_{th}}$
Parallel connection of electrical capacities: $C_{el} = C1_{el} + C2_{el} + \ldots + Cnel$	Parallel connection of heat capacities: $C_{th} = C1_{th} + C2_{th} + \ldots + Cnth$
Series connection of electrical capacities: $\frac{I}{C_{el}} = \frac{I}{C1_{el}} + \frac{I}{C2_{el}} + \ldots + \frac{I}{Cn_{el}}$	Series connection of heat capacities: $\frac{I}{C_{th}} = \frac{I}{C1_{th}} + \frac{I}{C2_{th}} + \ldots + \frac{I}{Cn_{th}}$
Electric current: $I(t) = Cel\left(\frac{dU}{dt}\right)$ $I(t) = \frac{U(t)}{R_{el}}$ $I(t) = U(t) \text{ x } G_{el}$	Heat flow: $\Phi(t) = \Delta T(t) \text{ x } G_{th}$ $\Phi(t) = \frac{\Delta T(t)}{R_{th}}$ $\Phi(t) = Cth\left(\frac{dU}{dt}\right)$

Note:

3) The contents of this table are from *Technische Temperaturmessung: Volume I*, Frank Bernhard, ISBN 978-3-642-62344-8.

Thermal Resistance (θ_{JA} and θ_{JC}) in a Datasheet

We will use the MPQ4572, a DC switching power IC from MPS, as an example for understanding thermal parameters in the datasheet.

Figure 1 shows two specified thermal resistance parameters: θ_{JA} and θ_{JC}.

Thermal Resistance	θ_{JA}	θ_{JC}	
QFN-12 (2.5mmx3mm)			
JESD51-7 (3)	60	13	°C/W
EVQ4572-QB-00A (4)	45	11	°C/W

3) Measured on JESD51-7, 4-layer PCB.
4) Measured on MPS standard EVB: 8.9cmx8.9cm, 2oz copper thick, 4-layer PCB.

Figure 1: Thermal Resistance (θ_{JA} and θ_{JC}) Specifications in a Datasheet

Thermal Resistance (θ_{JA} and θ_{JC}) in a Datasheet

Figure 2 shows a typical MPQ4572 application circuit with a 5V/2A output.

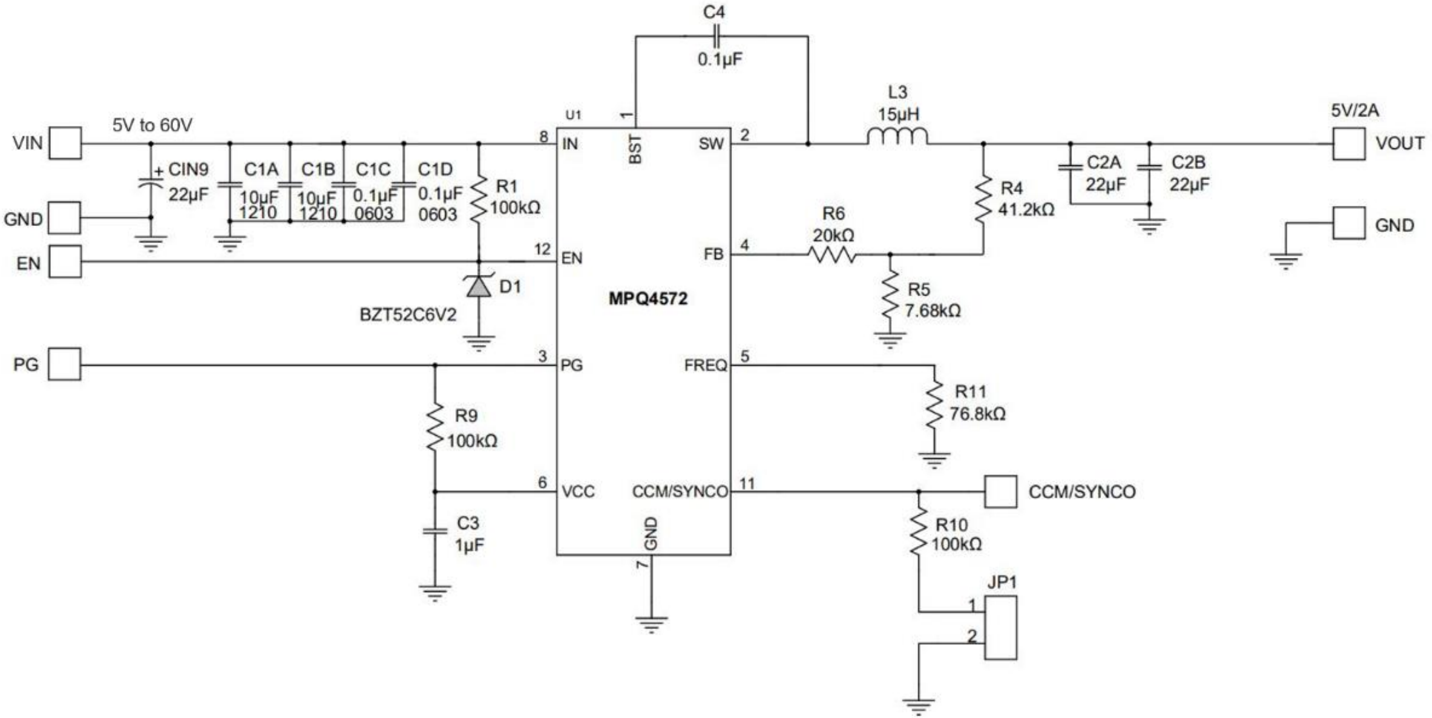

Figure 2: MPQ4572 Typical Application Circuit with a 5V/2A Output

What Is the Junction-to-Ambient Thermal Resistance (θ_{JA})?

$\boldsymbol{\theta_{JA}}$ is defined as the thermal resistance from the junction to ambient temperature. It is a measure of the device's ability to dissipate heat from the junction to ambient temperature via all heat transfer paths, the sum of copper tracks, vias, and air convention conditions.

$\boldsymbol{\theta_{JA}}$ is only valid for its defined PCB. It is a common mistake to believe that θ_{JA} is a constant that can be used on all PCBs.

$\boldsymbol{\theta_{JA}}$ allows for comparison of different packages on a common PCB, such as a JEDSD51-7.

The MPQ4572 is on a 4-layer JESD51-7 PCB [(1)]. Its θ_{JA} can be calculated with Equation (1):

$$\theta_{JA} = 60\,\frac{K}{W} \qquad (1)$$

Note:

1) JESD51-7 is a 4-layer, 114.3mmx76.2mm PCB, and is a highly effective thermal conductivity test board for leaded surface-mount packages. Its measurement method is available on https://www.jedec.org/.

What Is the Junction-to-Ambient Thermal Resistance (θ_{JA})?

If the MPQ4572 is on a 4-layer, 2oz. copper MPS test PCB (8.9cmx8.9cm), its θ_{JA} can be calculated with Equation (2):

$$\theta_{JA} = 45\,\frac{K}{W} \qquad (2)$$

As an example, the EVQ4572-QB-00A evaluation board has a 1.1W dissipation when R_T = 25°C. With a JESD51-7 board, the junction temperature (T_J) can be estimated using Equation (3):

$$T_J = 60\text{ x }\frac{K}{W}\text{ x }1.1W + 25°C = 91°C \qquad (3)$$

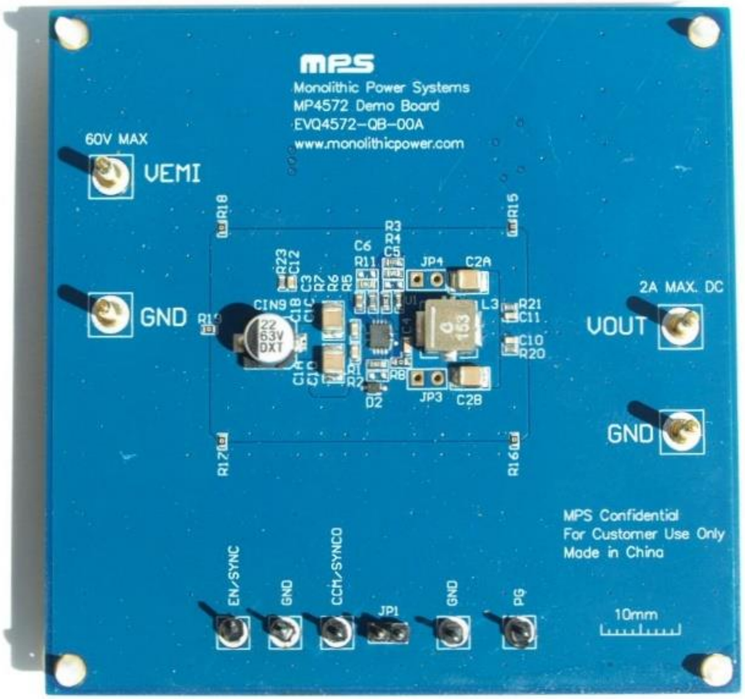

Figure 3: The EVQ4572-QB-00A Evaluation Board

What Is the Junction-to-Case Thermal Resistance (θ_{JC})?

θ_{JC} is defined as the thermal resistance from the junction-to-case temperature on the bottom of the package. This temperature is measured close to the pins. Calculate the junction temperature using θ_{JC} and Equation (4):

$$\mathbf{T_J = (\theta_{JC}\ x\ Heatflow_{JC}) + TC} \qquad \textbf{(4)}$$

Where $Heatflow_{JC}$ is the heat flowing from the junction to case, and can be estimated with Equation (5):

$$\mathbf{Heatflow_{JC} = Heatflow_{TOTAL} - Heatflow_{JT}} \qquad \textbf{(5)}$$

Where $Heatflow_{JT}$ is the heat flowing from the junction to the top surface.

What Is the Junction-to-Case Thermal Resistance (θ_{JC})?

Figure 4 shows why θ_{JC} cannot be used as a measurement on a custom PCB.

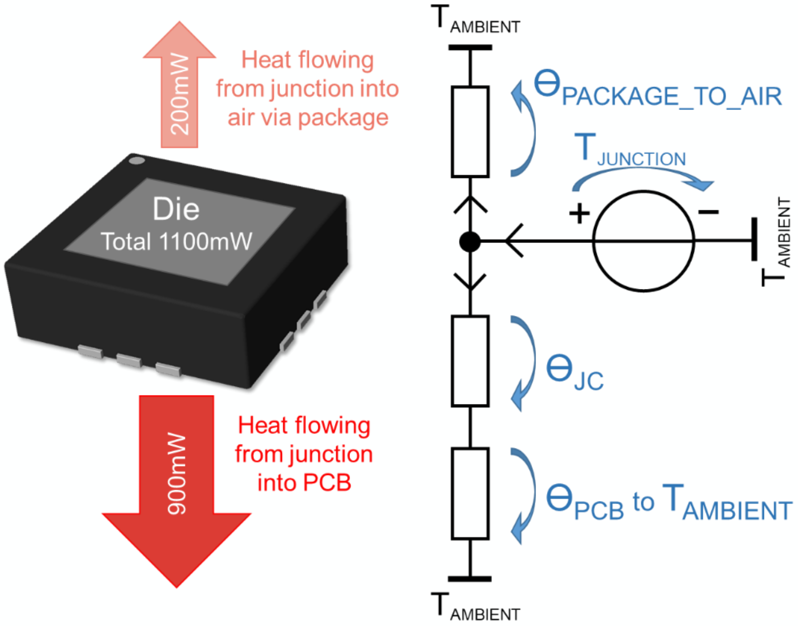

Figure 4: Junction-to-Case Thermal Resistance (θ_{JC})

- A custom PCB can be any dimension, different from a JESD51-7 PCB with 114.3mmx76.2mm dimensions.
- The purpose of θ_{JC} is to compare the ability to transmit the heat of different packages, measured on a JEDSD51-7 PCB.
- The actual heat flowing from a custom PCB package is unknown, whereas a JEDSD51-7 PCB has already had this parameter measured.
- In the example, heat flow is separated in two paths:
  - θ_{JC} unknown for the custom PCB
  - Heat flow that radiates via convection from the surface of the package to the environment

What Are the Thermal Characterization Parameters for the Junction-to-Case Top (Ψ_{JT}) and Junction-to-Board (Ψ_{JB})?

The name of the Greek letter Ψ is psi. Ψ_{JT} and Ψ_{JB} are described in JESD51-2A. Psi can be used when the designer knows the total electrical device power. Device power is often easy to measure, and by calculating it with psi, the user can directly calculate a board's junction temperature.

Ψ_{JT} and Ψ_{JB} are virtual parameters characterized by a measurement under a specified environment. The junction temperature can be calculated with Equation (6):

$$T_J = \Psi_{JT} \times P_{DEVICE} + T_{SURFACE} \qquad (6)$$

Where $T_{SURFACE}$ (°C) is the temperature on top of the package, and P_{DEVICE} is the electrical power in the IC.

Equation (6) uses the device's total power dissipation. This means that it is not necessary to know the power distribution between the package top and pins. This is an advantage of using thermal characterization parameters instead of θ_{JC}.

What Are the Thermal Characterization Parameters for the Junction-to-Case Top (Ψ_{JT}) and Junction-to-Board (Ψ_{JB})?

- A typical value for Ψ_{JT} is between 0.8°C/W and 2.0°C/W.
- Smaller packages tend to have a lower Ψ_{JT}, whereas larger packages with a thicker mold compound have a greater Ψ_{JT}.
- Estimate the difference between theta (θ) and psi (Ψ) with Equation (7) and Equation (8), respectively:

$$\theta_{12} = \frac{T_{POSITION\ 1} - T_{POSITION\ 2}}{Power_{PATH12}} \qquad (7)$$

$$\Psi_{12} = \frac{T_{POSITION\ 1} - T_{POSITION\ 2}}{P_{DEVICE}} \qquad (8)$$

Calculation with Thermal Networks

Figure 5 shows a thermal network that can be converted into an equivalent linear electrical network. θ_{JA} is the typical name for the equivalent thermal resistance between the junction and ambient air.

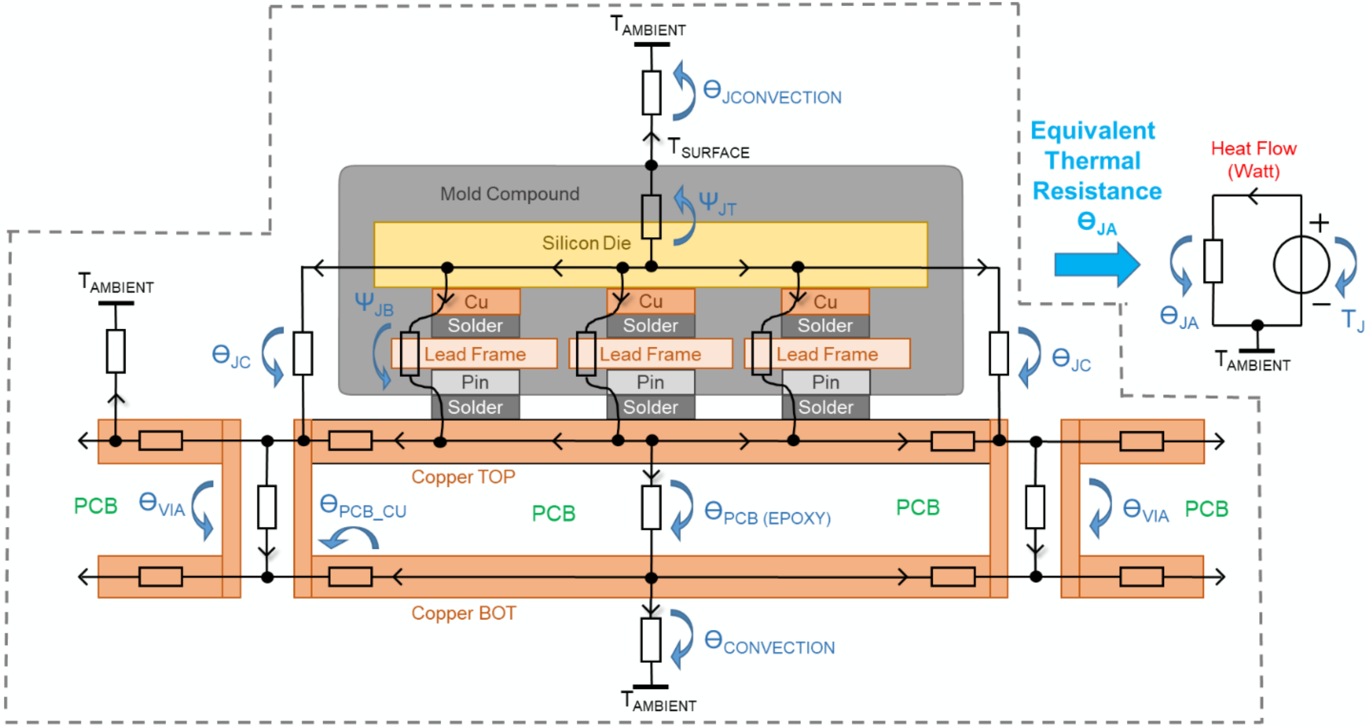

Figure 5: Drawing of a Thermal Network of an IC and a PCB

Calculation with Thermal Networks

- Thermal resistance (°C/W), heat flow (in W), and temperature difference (in Kelvin) describes ➔ thermal steady state.
- Adding the heat capacities (Ws/K), ➔ transient response.
- The level of detail increases the network ➔ complex calculations.
- Hardware developer lacks precise information about dimensions, material constants, and heat flow ➔ difficult to calculate.
- Layout and thermal programs can graphically represent the heat distribution via a finite element calculation ➔ good choice to avoid larger mathematical calculations.

Layout Recommendations

- Make the metallic heat transfer path between the IC and copper plane as short as possible.
- Two points with a large temperature difference

  ➔ best heat transfer path.
- VIA1 has a higher copper temperature difference between the top and bottom layers than the colder VIA2 (see Figure 6).
- VIA1 can transport a greater heat flow between both layers than VIA2 ➔ more effective cooling.
- Vias placed close to the package ➔ most effective.

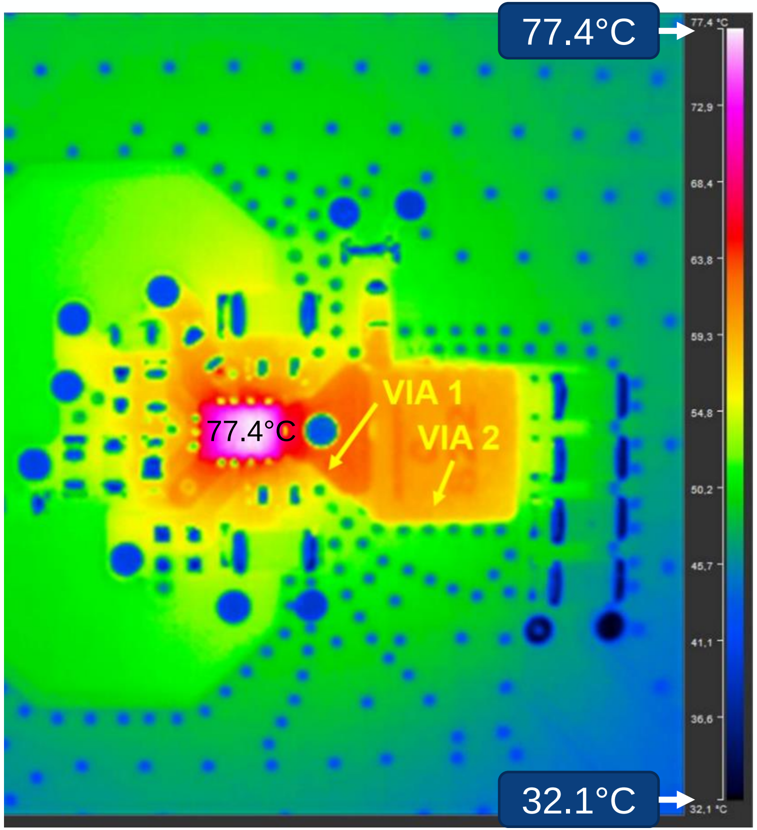

Figure 6: Thermal Image of a DC Switching Power IC

Layout Recommendations

- Large copper heat path near the IC.
- Avoid cutting planes with unnecessary conductor tracks.
- TOP and BOT layers are best to radiate heat.
- Avoid thermal reliefs on the SMT pads.
- Vias improve heat flow between layers.
- GND and stable potentials are best places for thermal vias.
- Filled, capped vias directly under the SMT pads improve thermal conductivity.
- Avoid vias for fast signals (switching node), which worsen EMC performance.
- PCB FR4 epoxy resin and glass fiber have low thermal conductivity.
- Certain PCB materials are 4 to 8 times more thermally conductive than FR4.

Conclusion

- The MPQ4572 from MPS was used to show how thermal parameters are analogous to electrical quantities and networks, and that both can be converted into one another.
- The electrical quantities often used by engineers enable a quick understanding of thermal parameters in the interactions between a PCB, a semiconductor, and their environment.
- Thermal resistance parameters (θ_{JA} and θ_{JC}), which are commonly listed in a device's datasheet, allow designers to compare between the thermal characteristics of different packages.
- Characterized thermal resistance (Ψ_{JT} and Ψ_{JB}) allows designers to calculate the junction temperature for custom applications.
- A temperature measurement on the top of the IC's surface makes it simple to obtain an accurate junction temperature.

Q&A

Let us know your questions

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