Thermal Design By Insight, Not Hindsight

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Introduction

All electronics contain; semiconductor devices, capacitors and other components that are vulnerable to thermally accelerated failure mechanisms. Thermal design becomes vital to improving the reliability of any design. Unfortunately, thermal design can be very difficult because of the mathematical analysis of fluid dynamics for complex geometries. Although this will remain true for the foreseeable future, this application note will cover the basics of thermal design for DC-DC converters using a simplified resistor model of heat transfer. We will focus on the thermal design for the semiconductor devices, but all of these techniques can be applied to other components. The resistor model is very useful for quickly estimating your design requirements, such as the PCB size and whether airflow is required. Finite element analysis software can then be used to analyze the design in more detail. The listed reference material is home to additional data and many useful thermal calculators, covering material that is beyond the scope of this application note.

Our discussion of thermal design will begin with the definition of parameters used in datasheets such as θ_{JA} and θ_{JC}, and end with some rules of thumb for the thermal design of a DC-DC converter, including their derivation. An accompanying spreadsheet (see References) uses these derivations to quickly provide a ballpark figure for the thermal performance of your design.

Definitions

Description of Thermal Terms

Parameters of interest : θ_{JA}, θ_{JC}, θ_{CA}, θ_{JT}

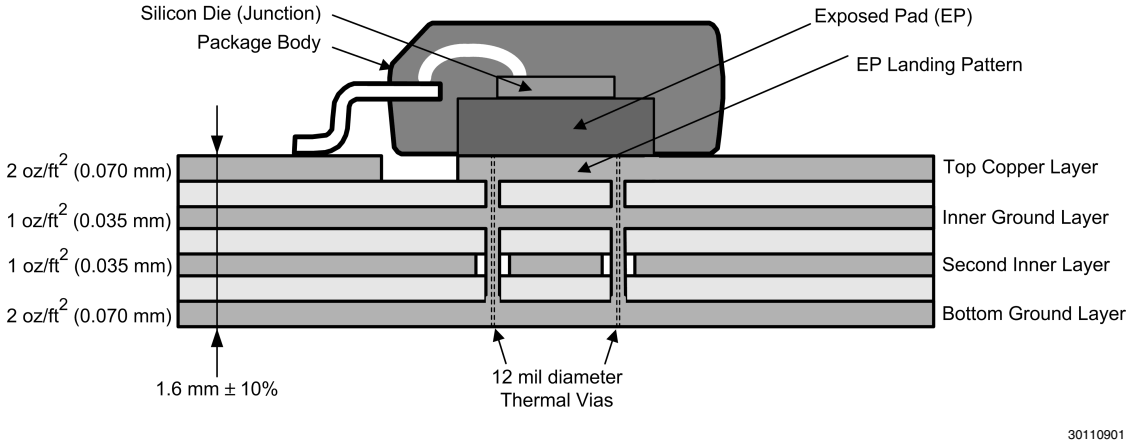


FIGURE 1. IC Mounted On A Four-Layer Printed Circuit Board

The most commonly specified parameter, in datasheets, for thermal performance is θ_{JA}. θ_{JA} is defined as the thermal impedance from the **J**unction, of the integrated circuit under test, to the **A**mbient environment. If we describe it using a resistor model, it is the parallel combination of all the paths that heat can take to move from the IC junction to the ambient air. The equation for this thermal resistance is:

$$\theta_{JA} = \frac{T_{JUNCTION} - T_{AMBIENT}}{\text{Power Dissipation}}$$

In our resistor model the heat transfer, measured in watts, takes the place of charge transfer measured in amps, and the temperature potential between the junction and ambient temperatures replaces the voltage potential. The heat that needs to be transferred away from the junction is the power dissipated by the IC.

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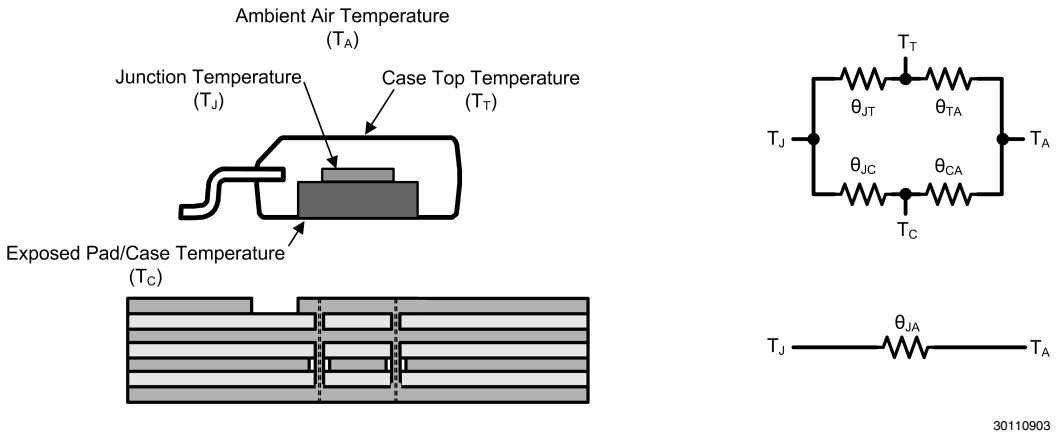


FIGURE 2. Simplified Thermal Resistance Model For A Typical PCB

There are two primary heat paths for a DC-DC converter represented above by their associated thermal resistances. The first path travels from the junction of the IC to the plastic molding at the top of the case (θ_{JT}) and then to the ambient air by convection/radiation (θ_{TA}). The second path is from the junction of the IC to an exposed pad (θ_{JC}). The exposed pad is then connected to the PCB, where the heat travels to the surface of the PCB and to the ambient air by convection/radiation (θ_{CA}).

There is one point of confusion that is common in defining θ_{JC}.

For DC-DC converters without an exposed pad, θ_{JC} is defined as the thermal impedance from the junction to the top of the case. This is in direct conflict with our previous definition of θ_{JC}, being the thermal impedance from the junction to the exposed pad. This confusion comes about because of the large number of packages that DC-DC converters have been shoved into over the years. As newer packages with exposed pads were released into the market it was decided that θ_{JC} should represent the lowest thermal impedance path from the junction of the IC to the outside world.

Now that we have cleared up the terminology, we can discuss the usefulness of various parameters.

Use the value of θ_{JA} given in the datasheet to compare different packages, and use it along with the IC power dissipation for a sanity check in your design. The high thermal resistance of the plastic packaging ensures that most of the heat travels from the exposed copper pad to the PCB, which usually has a much lower thermal resistance. A heat sink can be added to either the top of the package or directly beneath the exposed pad on the backside of the PCB. Again, because of the high thermal resistance of plastic, a heat sink will be more effective when connected to an exposed metal pad, either directly or, through thermal vias.

Since most of the heat transfer is through the exposed pad to the PCB it becomes immediately apparent that the value of θ_{JA} is highly PCB dependant. In other words, the most critical value to determine in any design is thermal resistance of the PCB (θ_{CA}). Well what, exactly, is θ_{CA} and how is it calculated? θ_{CA} is the equivalent resistance of a thermal resistive lattice that centers on the IC and ends at the surfaces of the board. It is the final of your freshman year, Circuits 101 class, all over again. *Figure 3* below shows the details.

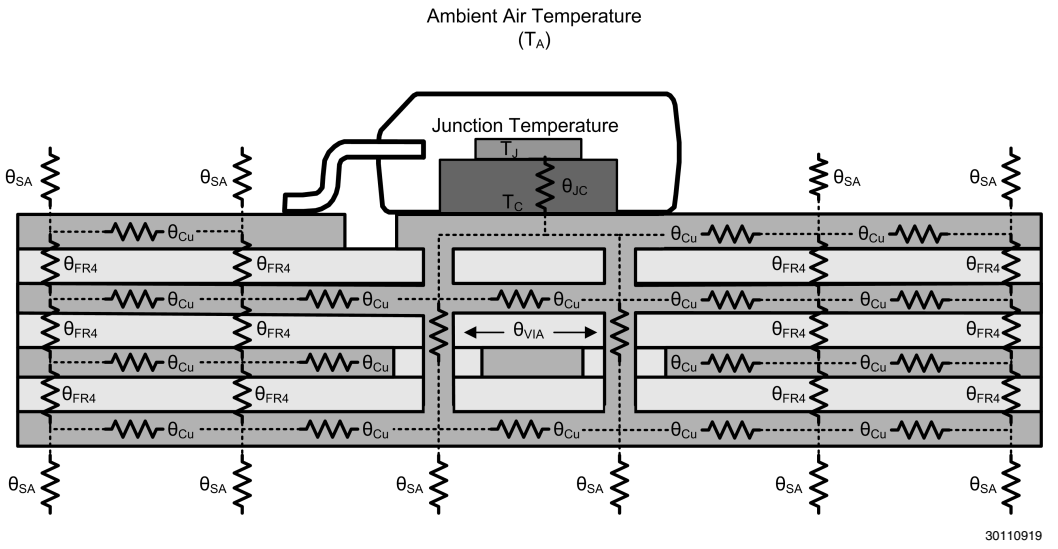


FIGURE 3. Expanded Thermal Resistance Model For A Typical PCB

There are new terms to add to our ever growing lexicon of θ's. θ_{Cu} is the thermal resistance of our board's copper to lateral heat transfer. θ_{FR4} is the thermal resistance between the copper planes provided by the vertical resistance of FR-4 laminate. θ_{VIA} is the thermal resistance of the thermal vias placed directly underneath the exposed pad. θ_{SA} is the thermal resistance from the surface of the PCB to the ambient air. It is a combination of convective and radiative heat transfer. If we break the board into 1 cm squares, the typical values for these resistances are listed below.

Typical Thermal Resistance Values

Name	Value	Description	Conditions	Equation
θ_{Cu}	71.4 °C / W	Lateral thermal resistance of copper plane.	Length = 1 cm, width = 1 cm, 1 ounce copper thickness = 0.0035 cm, thermal conductivity of copper (λ_{Cu}) = 4 W / (cm °C)	$\theta_{Cu} = \frac{\frac{1}{\lambda_{Cu}} \times \text{Length}}{\text{Area}} = \frac{0.25 \frac{°C\ cm}{W} \times 1\ cm}{1\ cm \times .0035\ cm}$
θ_{VIA}	261 °C / W	Thermal resistance of typical 12 mil via.	Via length = 0.165 cm (65 mils), 0.5 ounce copper plating thickness = 0.00175 cm, drill hole radius = 6 mil (0.01524 cm), thermal conductivity of copper (λ_{Cu}) = 4 W / (cm °C)	$\theta_{VIA} = \frac{\frac{1}{\lambda_{Cu}} \times \text{Length}}{\text{Area}} = \frac{0.25 \frac{°C\ cm}{W} \times 0.165\ cm}{\pi \times [(0.01524\ cm)^2 - (0.01524\ cm - 0.00175\ cm)^2]}$
θ_{SA}	1000 °C / W	Thermal resistance from the surface of a 1 cm square of the PCB to the ambient air due to natural convection.	1 cm square, a first order approximation of the heat transfer coefficient of PCB Board to Air for natural convection is (h) = 0.001 W / (cm^2 °C)	$\theta_{SA} = \frac{\frac{1}{h}}{\text{Surface Area}} = \frac{1000 \frac{°C\ cm^2}{W}}{1\ cm \times 1\ cm}$
θ_{FR4}	13.9 °C / W	Vertical thermal resistance of FR-4 substrate.	1 cm square, FR-4 thickness = 0. 032 cm (12.6 mil), thermal conductivity of FR-4 (λ_{FR4}) = 0.0023 W / (cm °C)	$\theta_{FR4} = \frac{\frac{1}{\lambda_{FR4}} \times \text{Thickness}}{\text{Area}} = \frac{435 \frac{°C\ cm}{W} \times 0.032\ cm}{1\ cm \times 1\ cm}$

The amount of variability in PCB designs is significant. You can see that the thermal resistance depends on board size, airflow, PCB thickness and many other parameters. For this reason, a series of JEDEC standards (JESD51-1 to JESD51-11) were developed, which specify the PCB size and layout for testing θ_{JA} for different types of packages. DC-DC converters that are tested to these standards can be directly compared to one another. Always check the datasheet to see

what PCB parameters were used to measure θ_{JA}. Later on we will discuss some tips for designing your PCB, but the final design, and thus θ_{JA}, depends on the end user.

EXAMPLE: CALCULATING YOUR REQUIRED θ_{JA}

Calculate the θ_{JA} required for a DC-DC converter with an output voltage, V_{OUT}, of 2.5V and output current, I_{OUT}, of 4 amperes. The converter efficiency, η, is 91.4%. The ambient temperature, T_A, is 50°C. The capacitors you selected are rated up to 100°C, and because of their proximity to the DC-DC converter you decide that the maximum junction temperature, T_J, you would like the converter to reach is 90°C.

The power dissipated by the converter, P_D, can be easily calculated.

$$P_D = V_{OUT} \times I_{OUT} \times \left(\frac{1}{\eta} - 1\right)$$

$$P_D = 2.5V \times 4A \times \left(\frac{1}{0.914} - 1\right) = 0.94W$$

Assuming that all of the power is dissipated internally to the IC, (a fair assumption if using LDOs or modules) we can now calculate the maximum value of θ_{JA}.

$$\theta_{JA} \leq \frac{90°C - 50°C}{0.94W} \leq 42.5\ °C/W$$

Since a θ_{JA} of less than 42.5°C / Watt is required for your design, you won't get there with a SOT-23 which has a θ_{JA} closer to 179°C / Watt. You would need to select a package like the 14 Pin eMSOP with a θ_{JA} of around 40°C / W. If you would like to increase the thermal margins for your design, pick a package like the TO-PMOD-7 or TO-263, which have θ_{JA}'s of around 20°C / W. Remember θ_{JA} is board dependant and all of these numbers come from using a JEDEC standard test board measuring 3" x 4". If your board varies from the JEDEC board, which it will, you will need to get a better estimate of thermal performance by using θ_{JC}, and deriving θ_{CA}.

A package with a low θ_{JC} will have very good heat transfer to the case, usually to an exposed pad. θ_{JC} is a very good indicator of a packages thermal performance. A low value for θ_{JA} implies a low value for θ_{JC}. The θ_{JC} for packages designed to dissipate large amounts of power can be less than 2°C / Watt. Typically, packages with no exposed pad have a θ_{JC} of greater than 100°C / Watt. That means that for every watt dissipated in the package the temperature difference between the junction of the IC and case will increase 100°C. If the value of θ_{JC} is not included in the datasheet it can often be requested from the manufacturer.

Rules of Thumb

PCB DESIGN to meet a given θ_{CA}

Parameters of interest: θ_{CA}

A low value for θ_{JC} (less than 10 °C / Watt) is a good start for a thermal design, but we still need to design a PCB or heat sink to transfer the heat from the case to the ambient air. This section will provide simple guidelines so that we can avoid calculating the full resistor model. The derivations for these rules of thumb will be discussed later.

RULE 1: BOARD SIZE

a)

$$\text{Board Area } (cm^2) \geq 15.29 \frac{cm^2}{W} \times P_D$$

$$\text{Board Area } (in^2) \geq 2.37 \frac{in^2}{W} \times P_D$$

With only natural convection (i.e. no airflow), and no heat sink, a typical two sided PCB with solid copper fills on both sides, needs at least 15.29 cm^2 (≅ 2.37 in^2) of area to dissipate 1 watt of power for a 40°C rise in temperature. Adding airflow can typically reduce this size requirement by up to half. To reduce board area further a heat sink will be required.

Several assumptions are made here. First, that any enclosure for the PCB does not restrict the natural convection of either side of the PCB. Second, that the PCB provides a low thermal resistance from the IC to the edges of the board. This can be accomplished by attaching the exposed pad to copper ground planes that extend to the edge of the PCB. With a four layer board, the internal ground planes can also be used to transfer the heat to the edges of the board. This can improve the thermal performance of even a well designed two-layer board by up to 30 percent.

b) The following equation can be used to approximate the minimum board size if θ_{JC} is known.

$$\text{Board Area } (cm^2) \geq \frac{500 \frac{°C \times cm^2}{W}}{\theta_{JA} - \theta_{JC}}$$

$$\text{Board Area } (in^2) \geq \frac{77.5 \frac{°C \times in^2}{W}}{\theta_{JA} - \theta_{JC}}$$

where θ_{JC} is obtained from the datsheet, and θ_{JA} is calculated from the power dissipation, ambient temperature, and maximum junction temperature as shown in the previous example.

EXAMPLE: CALCULATING THE REQUIRED BOARD SIZE TO HIT A TARGET θ_{JA}

Using our previous DC-DC converter example with V_{OUT} = 2.5, I_{OUT} = 4A, and P_D = 0.94W, we determined that a θ_{JA} = 42.5°C / W was necessary for the design.

a) Using the rule of thumb, with no airflow the PCB should be at least

$$\text{Board Area } (in^2) \geq 2.37 \frac{in^2}{W} \times 0.94W = 2.23\ in^2$$

b) Compare this to the equation using θ_{JC}. We determined that a 14 pin eMSOP would be a good choice for this design because the θ_{JA} is around 40°C / W on the JEDEC board. A 14 pin eMSOP has a θ_{JC} of ≅ 7.3°C / W. Using the equation we can calculate a minimum PCB area

$$\text{Board Area } (in^2) \geq \frac{77.5 \frac{°C \times in^2}{W}}{42.5 \frac{°C}{W} - 7.3 \frac{°C}{W}} = 2.2\ in^2$$

If we had picked a package that was not suitable to the task such a SOT-23 with a $\theta_{JC} \cong 100°C / W$, the answer would be negative telling us that there is no amount of board area that could be used to heat sink this device and meet the specifications.

However, if we had picked the TO-PMOD-7 package with $\theta_{JC} \cong 1.9°C / W$ we could have reduced the board size, or gained some margin for our design.

$$\text{Board Area (in}^2\text{)} \geq \frac{77.5 \ \frac{°C \times in^2}{W}}{42.5 \ \frac{°C}{W} - 1.9 \ \frac{°C}{W}} = 1.91 \ in^2$$

RULE 2: THERMAL VIAS

$$\theta_{VIAS} \approx \frac{261 \ \frac{°C}{W}}{\#\ \text{of Thermal Vias}}$$

A typical 12 mil diameter thru hole via with 0.5 oz copper sidewalls has a thermal resistance of 261 °C / Watt. Place as many thermal vias as will fit underneath the exposed pad to form an array, with 1mm spacing. Connect the vias to as many layers of copper as possible to spread the heat away from the package and to the PCB surface where it can transfer to the ambient air. For many DC-DC converters the exposed pad is electrically connected to ground and thus, the internal ground layer and the bottom ground layer are usually the most convenient copper planes for heat transfer. The thermal resistance is significantly lowered by having as solid a bottom layer ground as possible.

The thermal resistance of a via can be calculated using the following equation

$$\theta_{VIA} = \frac{\frac{1}{\lambda_{Cu}} \times \text{Length}}{\pi \times [(\text{radius})^2 - (\text{radius} - \text{plating thickness})^2]}$$

where $\lambda_{Cu} = 4$ W / cm K, the length is the thickness of the board (0.1561 cm typ), the radius is the radius of the drill hole (0.1524 cm typ), and the plating thickness = 0.0035 cm multiplied by the copper weight in ounces.

EXAMPLE: THERMAL IMPEDANCE OF VIA ARRAY

Using the 14 pin eMSOP. The exposed pad measures 3.1 x 3.2 mm. This would allow us to fit 16 thermal vias underneath the exposed pad of the device using 1mm spacing. Connect the vias to the copper ground layers to spread the heat. The thermal resistance of this 4 x4 array would be approximately 261 / 16 = 16.3°C / W

There are many advocates of completely plating closed the thermal vias to improve the thermal performance. A typical 8 mil diameter plated closed via has a thermal resistance of 128°C / W. The thermal resistance of the 16 vias in parallel is 128 / 16 = 8°C / W. The improvement in heat transfer to the bottom of the package is considerable, but it is usually not worth the cost. Plating closed the thermal vias can double or triple the cost of your PCB design. A more economical option is to ask for 1 oz plating on standard 12 mil vias, with perhaps a 10-20% cost adder. The thermal resistance of a single via is reduced to 140°C / W, and for a 4 x 4 array the thermal resistance is only 8.75°C / W.

Another option is to use a package with a larger exposed pad such as the TO-PMOD-7. The exposed pad measures 5.35 mm x 8.54 mm. This would allow us to place at least 40 vias. The thermal resistance of the via array using standard 12 mil vias is only 261 / 40 = 6.525°C / W.

RULE 3: COPPER THICKNESS

The thicker the copper in the board, the more easily heat can transfer away from the IC. The equation for the thermal resistance of a copper plane to lateral heat transfer is

$$\theta_{Cu} = \frac{\frac{1}{\lambda_{Cu}} \times \text{Length}}{\text{Width} \times \text{Thickness}}$$

where $\lambda_{Cu} = 4$ W / cm K, Length and Width are in centimeters, and copper Thickness = 0.0035 cm multiplied by the copper weight in ounces (0.5 oz. typical).

At least one ounce copper is recommended for all DC-DC converter designs. Two ounce copper is recommended for designs that dissipate more than 3 watts. Four ounce copper is recommended for designs that dissipate more than 6 watts.

To truly appreciate the value of thicker copper in a design we will look at the results for two "almost" identical two layer boards. The only difference is in the thickness of the copper. The first board has one ounce copper, and the second board has two ounce copper. Both boards measure 3 x 3" with minimal copper on the top layer where the component is placed, and the bottom layer completely filled with copper as a heat spreader. $\theta_{JA} = 28.3°C / W$ for the first board and 21.2°C / W for the board with thicker copper. This is a 25% improvement in the thermal performance of the board, by only changing the copper weight.

RULE 4: AVOID BREAKS IN THE THERMAL PATH

Maintain a copper ground plane on either the top or bottom copper layer with as few breaks as possible to create a heat spreader on the PCB. Spreading the heat across the PCB provides a low impedance path to the surface of the PCB and improves convective heat transfer. Traces perpendicular to the heat flow will create high impedances (speed bumps) for the heat and create hot spots (traffic jams). If traces through the copper heat spreader are unavoidable try to make them run parallel to the heat transfer, which flows radially from the heat source. The thermal image below *Figure 4* shows three almost identical boards with the same power dissipation. The only difference is a wide cut made on the top copper that breaks the thermal path. In the middle board, where the break is perpendicular to the heat flow this causes a 5.5 °C rise in temperature on an otherwise identical board. On the right hand board, where the break is parallel to the heat flow, the temperature rise is only 1.5 °C. This might make a serious difference if the board is pushing the thermal limits of the design.

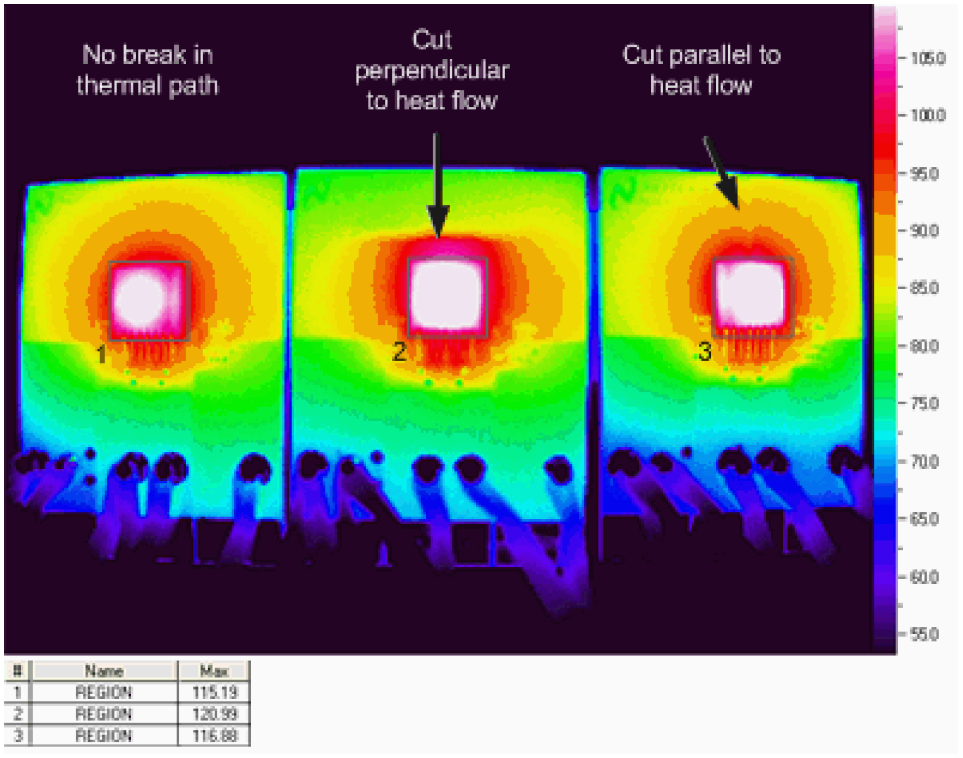


FIGURE 4. A Hot Spot Is Created When A Break Is Created In The Thermal Path

RULE 5: HEAT SINK PLACEMENT IS JUST AS IMPORTANT AS SELECTION

Heat sink selection must include the thermal resistance from the IC junction to the attachment point of the heat sink to be effective. For best performance a heat sink should be attached to the lowest impedance path to the IC junction.

EXAMPLE: HEAT SINK PERFORMANCE FOR DIFFERENT LOCATIONS

To understand rule 5 we will take a look at heat sink performance at two locations. If we again look at the TO-PMOD7, the package has a very low θ_{JC} = 1.35 °C / W. The thermal resistance to the top of the package is considerably higher because of the plastic interface. θ_{JT} can range from 50 to 200 °C / W for packages with a plastic top. A heat sink on top of the package is connected in series with the high thermal impedance of the plastic making the heat sink less effective. A heat sink on on the bottom of the board is connected in series with the low thermal impedance of the exposed pad and the relatively low thermal impedance of the vias making the heat sink more effective. To determine the effectiveness of a heat sink at the two locations, let's compare the resistive models.

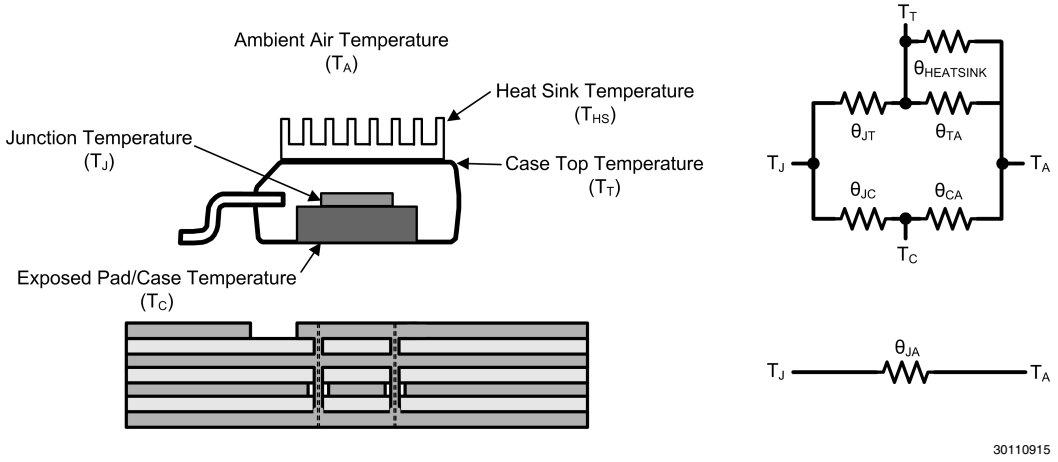


FIGURE 5. Thermal Resistance Model With Heat Sink Attached To The Package Top

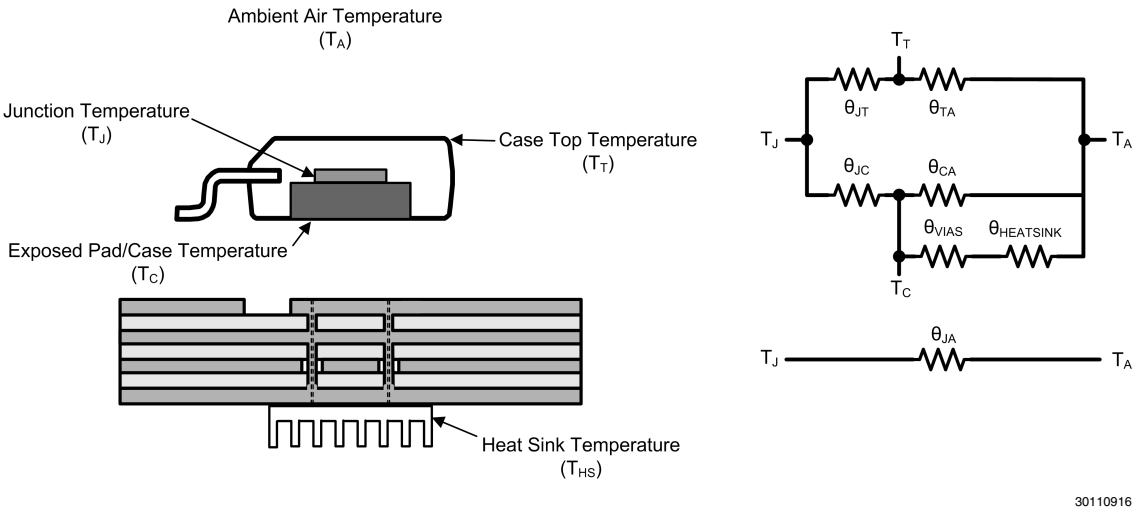


FIGURE 6. Thermal Resistance Model With Heat Sink Attached To Board Bottom

Newer mosfet packages are improving the thermal conductivity to the top of the package by having an exposed metal tab on the top. This style of package gives the user several heat sinking options.

RULE 6: MULTIPLE HEAT SOURCES: SUPERPOSITION ALMOST WORKS

If there are multiple heat sources in your design, how do you accomodate that? Well the good news is that superposition almost works. Almost? We are modeling the thermal environment as a resistive network with current sources (thermal resistances and power dissipation) therefore, we can use the superposition theorem, however, because some of those resistances have non-linear dependencies on temperature there will be some error in our final result.

To apply superposition to a system with multiple heat sources, solve for one heat source at a time, while leaving the others as open circuits in your system. Calculate the temperature rise at the locations of all the heat sources due to the other heat sources. The results can then be added together to get an estimate of the total temperature rise at the different locations.

Summary

Determining thermal performance is vital to any design, and should be considered before it becomes a problem. We have seen how some rules of thumb, derived through insight into thermodynamic principles, can be used at the beginning of the design process to help avoid drastic redesigns. Although this will not replace the accuracy of modern finite element analysis software, it will give you a starting point for the thermal design of your system.

Derivation of Rule 1 (Thermal Resistance from the Surface of the PCB to Ambient Air)

Heat transfer from the board to the ambient air is primarily by convection and radiation. A widely published figure for the heat transfer coefficient from the surface of the PCB (h) to air is 10 W / m^2K. We will use this as a starting point and look at the derivation of the heat transfer coefficient later.

To turn h into the thermal resistance from the board surface to the ambient air θ_{SA}, we take the inverse and then convert from square meters to square inches and finally divide by the surface area.

$$\theta_{SA} = \frac{\frac{1}{h}}{\text{Surface Area}} = \frac{0.1\ \frac{m^2\ K}{W}}{\text{Surface Area}} \times \frac{1550\ in^2}{1\ m^2} = \frac{155\ \frac{in^2\ K}{W}}{\text{Surface Area}}$$

The estimate used in rule one is easily derived from this if we assume that the thermal resistance from the junction of the IC to the surface of the PCB is small compared to θ_{SA}. The resistive model simplifies $\theta_{JA} = \theta_{JC} + \theta_{SA}$. If there is convective heat transfer from both sides of the board, θ_{SA} is reduced by half. A typical 14 pin eMSOP has a $\theta_{JC} \cong 7.3$. Therefore, to limit the IC junction temperature to a 40 degree rise in temperature for 1 W of power dissipation this translates to a required thermal resistance from board surface to ambient air of

$$\theta_{SA} = \frac{\theta_{JA} - \theta_{JC}}{P_D} = \frac{40^\circ C - 7.3^\circ C}{1W}$$

$$= 32.7\ \frac{^\circ C}{W}$$

The required board area is therefore

$$\text{Board Area} = \frac{155\ \frac{in^2 {}^\circ C}{W}}{2 \times \theta_{SA}} = \frac{155\ \frac{in^2 {}^\circ C}{W}}{2 \times 32.7\ \frac{^\circ C}{W}} = 2.37\ in^2$$

Calculating h

Now that you have seen the derivation for board area, we will revisit the derivation of the thermal transfer coefficient.

The thermal transfer coefficient can be calculated for forced convection with the following equation.

$$h = \frac{Nu \times \lambda_{AIR}}{\text{Length of Board}}$$

where λ_{AIR} = thermal conductivity of air ≅ 0.024 W / m K.

Nu, the Nusselt number, named after Wilhelm Nusselt, is a ratio of the convective to conductive heat transfer normal to a boundary layer. In our case the boundary is the surface of the PCB we are using to heat sink the DC-DC converter. The following correlation can be used to calculate the Nusselt number under laminar flow conditions.

$$Nu = 0.664 \times Re^{1/2} \times Pr^{1/3} \quad \text{for } Pr \geq 0.6$$

Pr, the Prandtl number, named after Ludwig Prandtl, is a ratio of Viscous diffusion to thermal diffusion. The higher the numbers the better a fluid is at convective heat transfer as compared to conductive heat transfer. Thus, a liquid metal such as mercury has a very low Prandtl number 0.015, and engine oil can be as high as 40,000. The Prandtl Number for air is between 0.7 and 0.8.

Re, the Reynolds number is a ratio of the inertial to viscous forces for a given flow condition. The Reynolds number can be used to determine the type of fluid flow. A laminar flow, characterized by lower Reynolds numbers, is smooth and constant. A turbulent flow, characterized by higher Reynolds numbers, where inertial forces are stronger than viscous forces, tends to have eddies and other flow instabilities. The following equation can be used to calculate the Reynolds number.

$$Re = \frac{\text{Fluid Velocity} \times \text{Density} \times \text{Length}}{\text{Viscosity}}$$

where Density = 1.184 kg / m^3 and

Viscosity = 1.98e-5 kg / m s.

Strictly speaking the Reynolds number should not be used as a measure of turbulence for natural convection. The Grashof number should be used (calculations below). However, I find that the simplicity of using only one equation for both natural and forced convection often outways the advantage of improved accuracy using the Grashof equation.

The velocity of air due to natural convection for a simplified vertical plate is

$$V_{NC} = 0.65 \times \left[g \times \text{Length} \times \frac{T_{BOARD} - T_A}{T_A}\right]^{1/2}$$

$$= 0.65 \times \left[9.8 \frac{m}{s^2} \times 0.0254m \times \frac{338K - 298K}{298K}\right]^{1/2}$$

The velocity of air due to natural convection ranges from 0.1 to 0.7 m/s for many PCB's, and for this calculation is 0.118 m / s. In my experience using a relatively high velocity of Vc = 0.5 m / s is a good starting point for a design and allows us to lump in the heat transfer from radiation and approximate the result using the Grashof number without making additional calculations.

Finally, after several calculations we find that the heat transfer coefficient from the surface of the PCB to the ambient air for a 0.0254m x 0.0254m (1 inch by 1 inch) board, with no forced airflow and air velocity from natural convection = 0.118 m / s is

$$h = 7.484 \text{ W / } m^2K$$

Once radiation is added to the heat transfer, (calculation shown below) this value is very close to the frequently published value (10 W / m^2K) used for the derivation of rule one.

Calculating Coefficienct Of Heat Transfer Using Grashof Number. Used For Natural Convection Calculations

Name	Value	Description	Conditions	Equation
Gr	8.77 x 10^4	Simplified equation for the Grashof number. Assumes ideal gas propeties.	Ta = 298 °K. Tboard = 338 °K, gravity = 9.8 m/s. Kinematic viscosity of air @ 25 °C = 15.68 x10^{-6} m^2 / s. Length of Board = 0.0254 m.	$Gr = \frac{g \times [T_{BOARD}^4 - T_A^4] \times Length^3}{T_A \times Kinematic\ Viscosity^2}$ $= \frac{9.8 \frac{m}{s^2} \times [(338\ K)^4 - (298\ L)^4] \times (0.0254\ m)^3}{298\ K \times (15.68 \times 10^{-6} \frac{m^2}{s^2})^2}$
Nu	14.39	Nusselt Equation for the two surfaces of a horizontal plate.	Pr = 0.7 for air at 25 °C.	$Nu = 0.54 \times (Gr \times Pr)^{1/4} + 0.15 \times (Gr \times Pr)^{1/3}$ $= 0.54 \times (8.77 \times 10^4 \times 0.7)^{1/4} + 0.15 \times (8.77 \times 10^4 \times 0.7)^{1/3}$
$h_{radiation}$	0.78 W / m^2 K	Thermal transfer due to radiation	Ta = 298 °K. Tboard = 338 °K, σ = 5.67 x 10^{-8}, e = 0.9, length of Board = 0.0254 m, width of Board = 0.0254 m.	$h_{RAD} = \frac{e \times \sigma \times [T_{BOARD}^4 - T_A^4]}{T_{BOARD}}$ $= \frac{0.9 \times 5.67 \times 10^{-8} \frac{W}{m^2 K^4} \times [(338\ K)^4 - (298\ K)^4]}{338\ K}$
h_{total}	14.38 W / m^2 K	Coefficient of heat transfer	Thermal conductivity of air (λ_{AIR}) = 0.024 W / (m °C), length of Board = 0.0254 m	$h = \frac{Nu \times thermal\ conductivity}{Length} + h_{RAD}$ $= \frac{14.39 \times 0.024 \frac{W}{m\ K}}{0.0254\ m} + 0.78 \frac{W}{m^2 K}$

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Notes

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