Freescale Semiconductor, Inc.

White Paper

Thermal Analysis of Semiconductor Systems

Contents

1 Introduction

Designing a cost competitive power electronics system requires careful consideration of the thermal domain as well as the electrical domain. Over designing the system adds unnecessary cost and weight; under designing the system may lead to overheating and even system failure. Finding an optimized solution requires a good understanding of how to predict the operating temperatures of the system's power components and how the heat generated by those components affects neighboring devices, such as capacitors and microcontrollers.

No single thermal analysis tool or technique works best in all situations. Good thermal assessments require a combination of analytical calculations using thermal specifications, empirical analysis and thermal modeling. The art of thermal analysis involves using all available tools to support each other and validate their conclusions.

This white paper first presents the basic principles of thermal systems and then describes some of the techniques and tools needed to complete such an analysis. Power devices and low lead count packages are the primary focus, but the concepts herein are general and can be applied to lower power components and higher lead count devices such as microcontrollers.

2 Definitions and Basic Principles

2.1. Definitions

A good way to begin a study of a domain is to familiarize oneself with its definitions, nomenclature and notations. The terms used for thermal analysis vary somewhat throughout the industry. Some of the most commonly used thermal definitions and notations are:

T_A	Temperature at reference point "A"
T_J	Junction temperature, often assumed to be constant across the die surface
T_C or T_{Case}	Package temperature at the interface between the package and its heatsink; should be the hottest spot on the package surface and in the dominant thermal path
ΔT_{AB}	Temperature difference between reference points "A" and "B",
q	Heat transfer per unit time (Watts)
P_D	Power dissipation, source of heat flux (Watts)
H	Heat flux, rate of heat flow across a unit area ($J \cdot m^{-2} \cdot s^{-1}$)
$R_{\Theta AB}$	Thermal resistance between reference points "A" and "B", or R_{THAB}
$R_{\Theta JMA}$	Junction to moving air ambient thermal resistance
$R_{\Theta JC}$	Junction to case thermal resistance of a packaged component from the surface of its silicon to its thermal tab, or R_{THJC}
$R_{\Theta JA}$	Junction to ambient thermal resistance, or R_{THJA}
$C_{\Theta AB}$	Thermal capacitance between reference points "A" and "B", or C_{THAB}
°C or K	Degrees Celsius or degrees Kelvin
$Z_{\Theta AB}$	Transient thermal impedance between reference points "A" and "B", or Z_{THAB}

The term "Junction Temperature"

The term junction temperature became commonplace in the early days of semiconductor thermal analysis when bipolar transistors and rectifiers were the prominent power technologies. Presently the term is reused for all power devices, including gate isolated devices like power MOSFETs and IGBTs.

Using the concept "junction temperature" assumes that the die's temperature is uniform across its top surface. This simplification ignores the fact that x-axis and y-axis thermal gradients always exist and can be large during high power conditions or when a single die has multiple heat sources. Analyzing gradients at the die level almost always requires modeling tools or very special empirical techniques.

Most of the die's thickness is to provide mechanical support for the very thin layer of active components on its surface. For most thermal analysis purposes, the electrical components on the die reside at the chip's surface. Except for pulse widths in the range of hundreds of microseconds or less, it is safe to assume that the power is generated at the die's surface.

2.2. Basic Principles

The basic principles of thermal analysis are similar to those in the electrical domain. Understanding one domain simplifies the task of becoming proficient in the other. This is especially clear when we consider thermal conduction. The two other thermal transport mechanisms are discussed later.

Each domain has a “through” and an “across” variable, as shown in Figure 1 and Table 1. The through variable can be thought of as the parameter that flows from one reference point to another. Current is the through variable for the electrical domain and power is the through variable in the thermal domain.

The across variable can be thought of as the variable that forces the flow of current or heat. In each domain the forcing function is a difference in potential; in one domain it’s temperature and in the other it’s voltage.

Both systems have a resistance that impedes the flow of the through variable.

Given the duality of the two systems, it is no surprise that the fundamental equations of the domains are similar. This is illustrated most clearly when we see that each system has an “Ohm’s Law”, as is shown in Table 1.

Figure 1—Fundamental Relationships in the Electrical and Thermal Domains

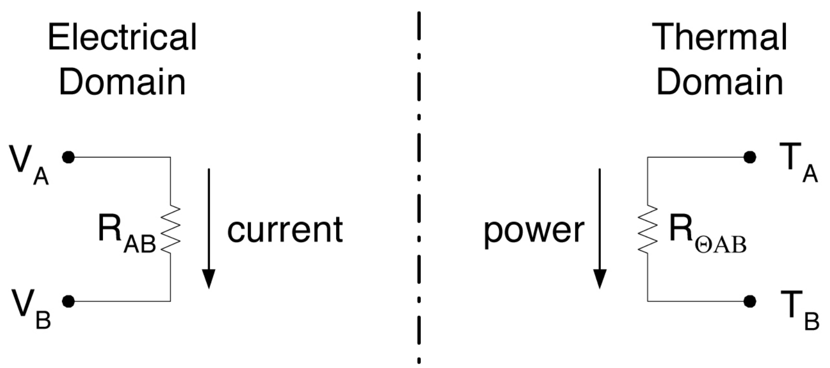


Table 1—Basic Relationships in the Electrical and Thermal Domains

	Electrical Domain			Thermal Domain		
	Variable	Symbol	Units	Variable	Symbol	Units
Through Variable	Current	I	Amperes or Coulombs/s	Power or Heat Flux	P_D	Watts or Joules/s
Across Variable	Voltage	V	Volts	Temperature	T	°C or K
Resistance	Electrical Resistance	R	Ohms	Thermal Resistance	$R_{\Theta AB}$	°C/W or K/W
Capacitance	Electrical Capacitance	C	Farads or Coulombs/V	Thermal Capacitance	C_Θ	Joules/°C
"Ohm's Law"	$\Delta V_{AB} = V_A - V_B = I * R_{AB}$			$\Delta T_{AB} = T_A - T_B = P_D * R_{\Theta AB}$ (derived from Fourier's Law)		

From the relationships above,

$$\Delta T_{JA} = (T_J - T_A) = P_D R_{\Theta JA}$$

we can easily derive the often used equation for estimating junction temperature:

$$T_J = T_A + (P_D R_{\Theta JA}) \quad \text{(Eq. 1)}$$

For example, let's assume that:

$R_{\Theta JA} = 30°C/W$
$P_D = 2.0W$
$T_A = 75°C$

Then, by substitution:

$T_J = T_A + (P_D R_{\Theta JA})$
$T_J = 75°C + (2.0W * 30°C/W)$
$T_J = 75°C + 60°C$
$T_J = 135°C$

A cautionary note is in order here. The thermal conductivities of some materials vary significantly with temperature. Silicon's conductivity, for example, falls by about half over the min-max operating temperature range of semiconductor devices. If the die's thermal resistance is a significant portion of the thermal stackup, then this temperature dependency needs to be included in the analysis.

2.3. Transient Thermal Response

Of course, the duality extends to transient as well as steady state conditions. The existence of capacitance in both domains results in thermal RC responses like those we are familiar with in the electrical domain. The basic relationships follow.

Thermal time constant is equal to the thermal R-C product, that is:

$$\tau_\Theta = R_\Theta C_\Theta \quad \text{(Eq. 2)}$$

Thermal capacitance is a function of the temperature rise associated with a given quantity of applied energy. The equation for thermal capacitance is:

$$C_\Theta = q\, t/\Delta T \quad \text{(Eq. 3)}$$

where:

q = heat transfer per second (J/s)
t = time (s)
ΔT = the temperature increase (°C)

Thermal capacitance is also a function of mechanical properties. It is the product of a material's specific heat, density, and volume:

$$C_\Theta = c\, d\, V \quad \text{(Eq. 4)}$$

where:

c = specific heat ($J\, kg^{-1}\, K^{-1}$)
d = density (kg/m^3)
V = volume (m^3)

Furthermore, the temperature of a thermal RC network responds to a step input of power according to:

$$\Delta T_{AB} = R_{\Theta AB} P_D (1 - e^{(-t/\tau)}) \quad \text{(Eq. 5)}$$

2.4. Convection and Radiation

Conduction is only one of three possible thermal transport mechanisms. In addition to conduction, the other mechanisms are radiation and convection. In fact, these other transport mechanisms often become the predominant ones as heat exits a module.

Radiation and convection are clearly more complex thermal transport mechanisms than conduction, and we will see that in their governing equations. Consider first convection, which occurs when a solid surface is in contact with a gas or liquid at a different temperature. The fluid's viscosity, buoyancy, specific heat and density affect the heat transfer rate from the solid's surface to the fluid. The surface's area and its orientation (i.e., horizontal or vertical) as well as the shape of the volume in which the fluid is free to circulate are additional factors. And, having the greatest effect is whether the system uses forced air (fan cooling) or natural convection.

Although convective behavior is quite complex, its descriptive equation is relatively simple and can be expressed as:

$$q = k\,A\,\Delta T \qquad \text{(Eq. 6)}$$

where:

- q = heat transferred per unit time (J/s)
- k (or h) = convective heat transfer coefficient of the process ($W\,m^{-2}\,°C^{-1}$)
- A = heat transfer area of the surface (m^2)
- ΔT = temperature difference between the surface and the bulk fluid (°C)

The convection coefficient, k, can be determined empirically, or it can be derived from some thermal modeling programs. It changes, for example, with air speed when a fan is used, with module orientation or with fluid viscosity.

Radiation is a completely different process and augments the other two transport mechanisms. Quantifying heat transferred by radiation is complicated by the fact that a surface receives as well as emits radiated heat from its environment. "Gray Body" (vs. "Black Body") radiation is the more general condition and its governing formula is:

$$q = \varepsilon\,\sigma\,A\,(T_h^4 - T_c^4) \qquad \text{(Eq. 7)}$$

where:

- q = heat transfer per unit time (W)
- ε = emissivity of the object (one for a black body)
- σ = Stefan-Boltzmann constant = $5.6703 \cdot 10^{-8}$ ($W\,m^{-2}\,K^{-4}$)
- A = area of the object (m^2)
- T_h = hot body absolute temperature (K)
- T_c = cold surroundings absolute temperature (K)

Exercising Equation 7 shows that for geometries and temperatures typical of semiconductor packages, radiation is not a primary transport mechanism. But at the module level, because of the much larger surface area and the heat transfer's dependence on the 4th power of temperature, radiation can play a much more important role. Nevertheless, for larger objects thermal radiation is often accounted for by including its effect in a general thermal resistance value. But since radiation is a strong function of temperature, this practice is acceptable only over a modest range of module and ambient temperatures or when the module and ambient temperatures are nearly the same.

Applying three different and sometimes complex thermal transport mechanisms to a complex thermal circuit creates a system that cannot be evaluated by simple and inexpensive tools. Often the only feasible approach is to model a thermal circuit with tools created for that purpose and validate that model with empirical testing.

3 Differences between Electrical and Thermal Domains

Considering how the electrical and thermal domains differ is a good way to avoid some common misconceptions and misunderstandings. One key difference between the domains is that in the electrical domain the current is constrained to flow within specific circuit elements, whereas in the thermal domain heat flow is more diffuse, emanating from the heat source in three dimensions by any or all of the three thermal transport mechanisms. In electrical circuit analysis current is limited to defined current paths and that allows us to use lumped circuit elements, such as resistors, capacitors, etc. But in the thermal domain the thermal path is not so constrained, so using lumped elements is not as appropriate. Even in relatively simple mechanical systems, defining lumped thermal components is often an exercise in estimation, intuition and tradeoffs. We want to use lumped elements to model our thermal systems, but we must remember that to do so we've made many simplifying assumptions.

A second major difference is that coupling between elements is usually a more prominent behavior in the thermal domain. Isolating devices in electrical circuits is usually easier than isolating elements in thermal networks. Therefore, good thermal models usually employ thermal coupling elements, while many electrical circuits do not require them.

The tools to model complex systems are quite different between the domains. Electrical circuit analysis tools, such as SPICE, can be used for thermal circuits of lumped elements, but such tools are not appropriate for assessing how heat flows in a complex mechanical assembly.

The test and evaluation tools differ as well. You can't clamp a "heat flux meter" around a thermal element to monitor how much power passes through it. For thermal analysis infrared cameras and thermocouples replace oscilloscopes and voltage probes.

Even though the domains have their differences, they are likely to be interdependent. A prime example is the temperature dependence of a power MOSFET's on-resistance, which increases by 70 to 100 percent as the temperature increases from 25ºC to 150ºC. The higher on-resistance increases power dissipation, which elevates temperature, which increases on-resistance, and so on.

4 Thermal Ratings

4.1. Thermal Resistance Ratings

Now let's investigate how these basic thermal relationships affect manufacturers' thermal resistance specifications. For a given package style, for example the SOIC, thermal performance can vary substantially depending on the package's internal construction and how the system extracts heat from the package leads or its body. Figure 2 shows that the standard SOIC's leadframe floats within the package's mold compound, so there is no direct low impedance thermal path from the die to that package's surface. Heat generated in the die readily travels into the leadframe, but then it struggles to move through the mold compound to the package surface and through the wirebonds to its leads. Even though heat travels only a short distance, the package's thermal resistance is high due to the mold compound's high thermal resistivity and the wirebonds' very small cross sectional area.

The portion of the leadframe on which the die is placed is called the "die paddle," or "flag." The package's thermal performance can be enhanced substantially by improving the thermal path from the paddle to the package's surface. One way to do this is to stamp the leadframe so that some of the leads are directly connected to the die paddle (flag). This allows heat to flow relatively unimpeded through the "thermally enhanced" leads and onto the PCB. Another approach is to expose the die paddle at the bottom (or top) of the package. This structure yields a much more direct thermal path and vastly improves the device's thermal performance.

Since the primary thermal path differs with modifications in the package construction, each variation merits its own thermal reference points and, therefore, its unique thermal resistance specifications.

Table 2 contains thermal resistance ratings of two devices with essentially the same die. Both use a version of the 32-lead, fine-pitch, wide-body SOIC. One version has an enhanced leadframe (the two centermost leads on each side of the package are directly connected to the die pad), and the other has an exposed pad on the IC's belly. Their internal construction and how they are typically mounted on a PCB are shown in Figure 3.

Figure 2—Cross Sections of standard and exposed pad SOICs

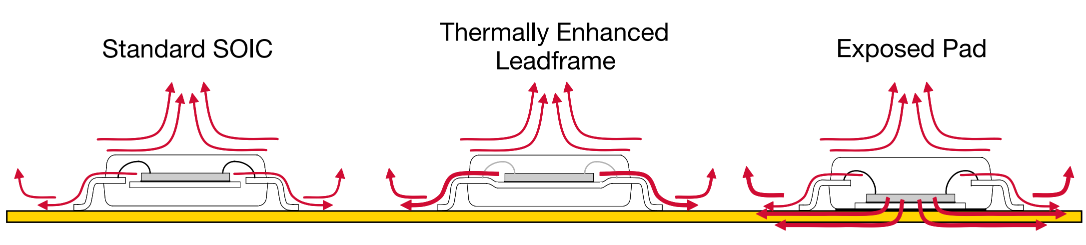
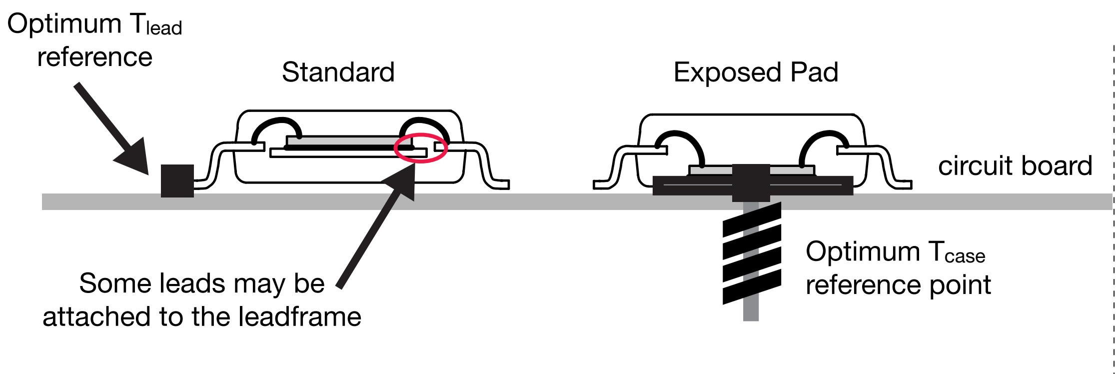


Table 2—Typical Thermal Resistance Specifications

Thermal Ratings	Symbol	Value		Unit
		Standard 32 lead SOIC Case 1324-02	Exposed pad 32 lead SOIC Case 1437-02	
Thermal Resistance Junction to Case Junction to Lead Junction to Ambient	$R_{\theta JC}$ $R_{\theta JL}$ $R_{\theta JA}$	- 18 70	1.2 - 71	°C/W

Figure 3—Cross Sections of standard and exposed pad SOICs



For the standard SOIC the primary path for heat flux is laterally through the wirebonds and the mold compound, into the leads and then vertically into the board. For the exposed pad package the path is much more direct; heat passes vertically through a broad cross section from the top of the die through the silicon, through the die attach material, through a leadframe and another solder layer then into the circuit board. The difference in thermal paths between the two options is in the tens of °C/W.

However, the alert reader will note that the junction to ambient thermal resistances of the two SOIC package options is essentially the same even though one is clearly thermally superior. How is this possible? The reason is that each device is characterized on a worst case board, that is, one that has minimum heatsinking on the board. Without measures to disperse heat, the advantage of the exposed pad package is lost.

But the important point here is that each device merits its own thermal rating based on its primary thermal path. The standard SOIC merits a junction-to-lead specification, whereas the exposed pad device requires a junction-to-case rating. Junction-to-case ratings, therefore, are most appropriate for devices whose primary thermal path is through an exposed thermal tab, not through the leads. The moral of the story is that the user should carefully note the reference points used for a device's thermal resistance specifications and correctly apply those specifications to the application.

Semiconductor manufacturers are adept at specifying their devices' thermal performance. But users want more. They want to know what performance they can expect when the device is used as intended, that is, mounted to a board and possibly attached to a heatsink. Unfortunately, thermal performance depends strongly on how the device is mounted and used, and there is a vast array of possibilities. So there is no single set of test conditions for a universally applicable characterization. In order to provide some characterization, manufacturers specify thermal behavior for worst case mounting conditions or conditions typical of the application. Users must relate the test data and specifications to their particular thermal environment.

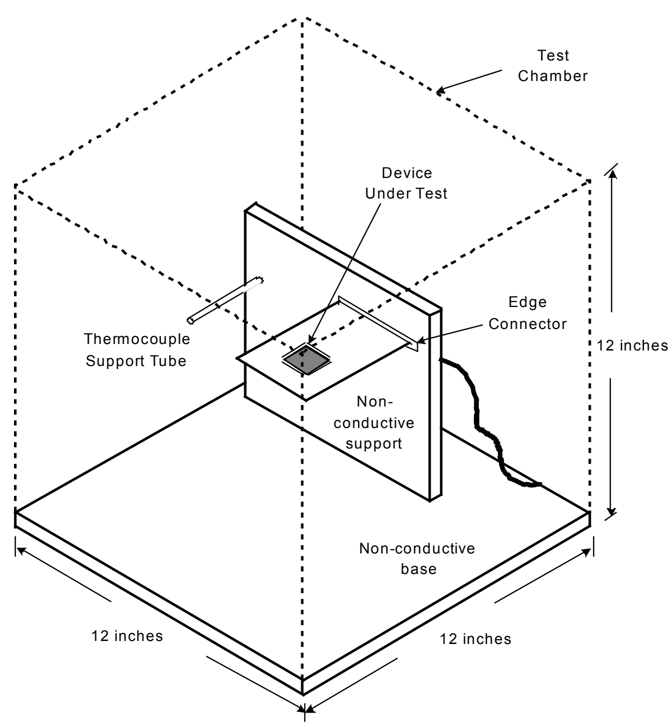
4.2. JEDEC Test Methods and Ratings

JEDEC Solid State Technology Association (once known as the Joint Electron Device Engineering Council) is the semiconductor engineering standardization body of the Electronics Industries Alliance (EIA). They have published thermal characterization test methods and standards that apply to a wide variety of semiconductor packages, mountings and usages. The recommendations in their JESD51 series of publications underpin many of the manufacturers' thermal specifications. A list of the JESD51 publications is provided in Appendix A

Among their many contributions, several stand out for the thermal characterization of power electronic devices:

1. Created a standard for electrically measuring thermal resistance using a temperature sensitive parameter (TSP). This method can be used to determine steady state behavior or transient response. (JESD51-1)
2. Defined a test method for J-A measurement for still air. This method tests the device on a PCB suspended in a one cubic foot chamber, shown in Figure 4. (JESD51-2)

Figure 4—Test chamber as recommended in JESD51-2



3. Identified and standardized the thermally relevant features of circuit boards used in J-A characterization. Defined features including board material, dimensions, trace design, via features, etc., as shown in Figure 5. (JESD51-3)
4. Defined standards for forced convection testing (moving air) and standardized the term Θ_{JMA}, junction to moving air thermal resistance. (JESD51-6)
5. Specified standards for "low" and "high" thermal conductivity boards. Popularized usage of the terms "1s" and "2s2p" printed circuit boards. (JESD51-3, 7)

Figure 5—JEDEC specified PCB for J-A thermal characterization

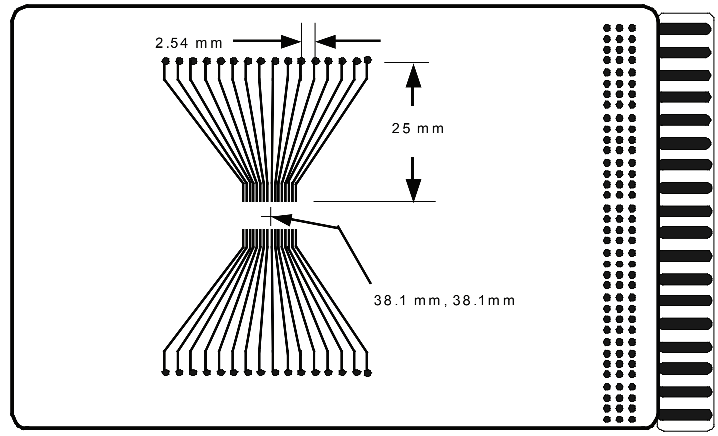


Figure 5 shows the PCB layout of a low thermal conductivity board. The intent is to characterize the J-A resistance under conditions of a worst case layout.

The 1s board has signal traces on the component side of the board, 70µm copper thickness and no internal power or ground planes. The JEDEC specification contains details of the board size and thickness, trace width and length, etc. The board is allowed to have some traces on the second side, but only if they are outside the fan-out area of the topside traces.

The 2s2p board has 70µm signal traces on the component side of the board and two internal planes with 35µm copper.

6. Created specifications for thermally enhanced circuit boards. (JESD51-7)
7. Specified thermocouple probe placement to match a particular test method and specification.
8. Standardized the terms for YJT (Psi-junction to top of package) and YJB (Psi-junction to board) to estimate the junction temperature based on the temperature at the top of the package. These are "thermal characterization parameters" and not true thermal resistances. (JESD51-2, 8, 10, 12)

From JESD51-12 we read, "Ψ_{JB} is the junction to board thermal characterization parameter where T_{Board} is the temperature measured on or near the component lead." And, "Thermal characterization parameters are not thermal resistances. This is because when the parameter is measured, the component power is flowing out of the component through multiple paths."

9. Posted usage guidelines and identified limitations of applying thermal specifications to actual thermal systems. (JESD51-12)

4.3. Thermally Enhanced Circuit Boards

Some commonly used techniques to improve thermal performance are not addressed in the JEDEC51 specifications. As illustrated in Figure 6, dedicated copper islands may be placed near heat generating components to conduct heat from the IC and to convect and radiate heat from the PCB's surface. Also, designers may attach a heatsink to the backside of the PCB or even the top of the package. PCB traces that conduct high current to power devices are commonly made as large as allowable so as to minimize ohmic heating and enhance heat flow. Heat generating devices are sometimes placed near other cooler components, such as connectors, transformers or capacitors, to improve dispersion. Modules designed for high power may very well have heavy copper cladding with vias to the back of the board or to internal copper planes. These measures and others can yield thermal resistances substantially lower than those obtained from the JEDEC specified tests.

The board illustrated in Figure 6 shows how a PCB might be modified to reduce thermal impedance. To help users optimize thermal layouts, many manufacturers specify thermal resistance with such thermally enhanced boards. These ratings usually include a curve of thermal resistance versus pad area, as shown in Figure 7.

Figure 6—Thermal resistance test board with dedicated thermal pad

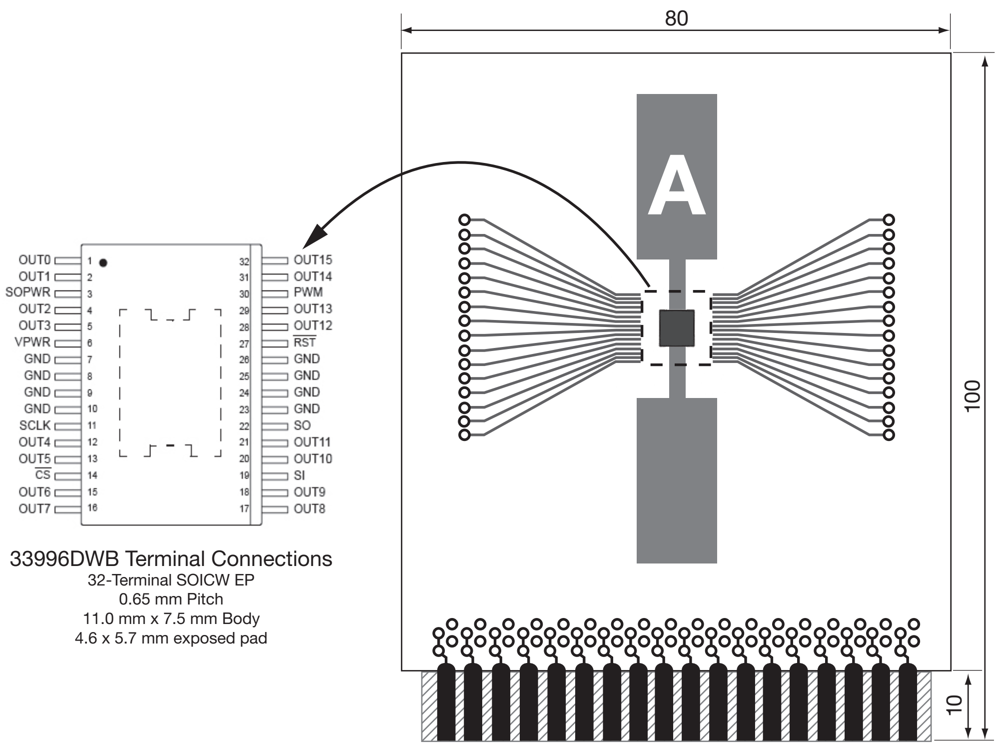
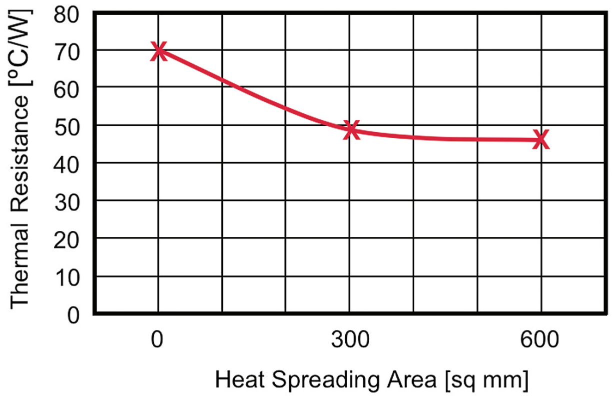


Figure 7—Junction to ambient thermal resistance decreases with dedicated thermal pad area

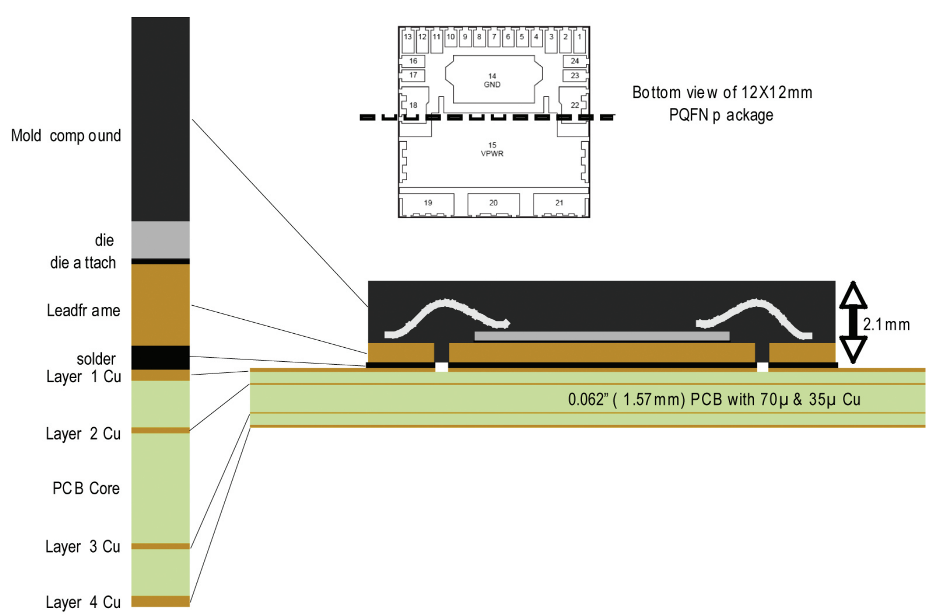


Another style of exposed pad package is the PQFN (power QFN). It is a relatively new leadless power package and the 12mm by 12mm, 24-terminal version is shown in Figure 8. The power die is soldered to the largest pad. The figure also shows a cross section of the PQFN package mounted on a 0.062" PCB. The illustrated 2s2p board has 2 ounce/ft2 copper on the top and bottom layers (70µm thick) and 1 ounce/ft 2 copper (35µm) on the two inner layers. This figure illustrates why layout is so important to thermal behavior.

Imagine two cases, each related to the top copper layer. The first uses continuous topside copper to draw heat from IC's exposed leadframe to the surrounding board area. You can also imagine vias connecting the topside copper to the other three layers. The second case has copper only beneath the PQFN's leadframe with no provision to conduct heat laterally. This results in a thermal barrier at the copper to PCB laminate interface. In the second case the thermal benefit of the exposed thermal pad is almost completely lost.

The figure also illustrates which structures of the thermal stackup contribute to thermal capacitance. The die, die attach, leadframe, solder and even the package's mold compound and the circuit board provide a reservoir for thermal transients. (Appendix B shows the thermal properties of common packaging materials.) These structures can absorb energy transients, but like electrical capacitance, their effectiveness drops to zero for steady state conditions. Since systems are commonly subjected to power transients, designers need to understand their system's dynamic as well as static thermal behavior.

Figure 8 —Cross section of a PCB and a PQFN package



4.4. Transient Thermal Response Ratings

In many systems the worst case conditions occur during a transient condition, such as when inrush current flows into a cold lamp filament, startup or stall currents appear in a motor or a short circuit causes fault current. The duration of such a transient could very well be far shorter than the system's thermal time constant, especially since we often use intelligent power devices to manage such events. If the system is designed to meet worst case transient conditions for an unnecessarily long time, the system will be over designed. Knowing how the system responds to thermal transients helps the designer size components and provide adequate, but not unnecessary, heatsinking.

When you include characterization in the time domain to the many possible ways to characterize a device in steady state, the possible options are too large to manage. To provide the most universally useful data, the industry has adopted and promoted a concept called "transient thermal response."

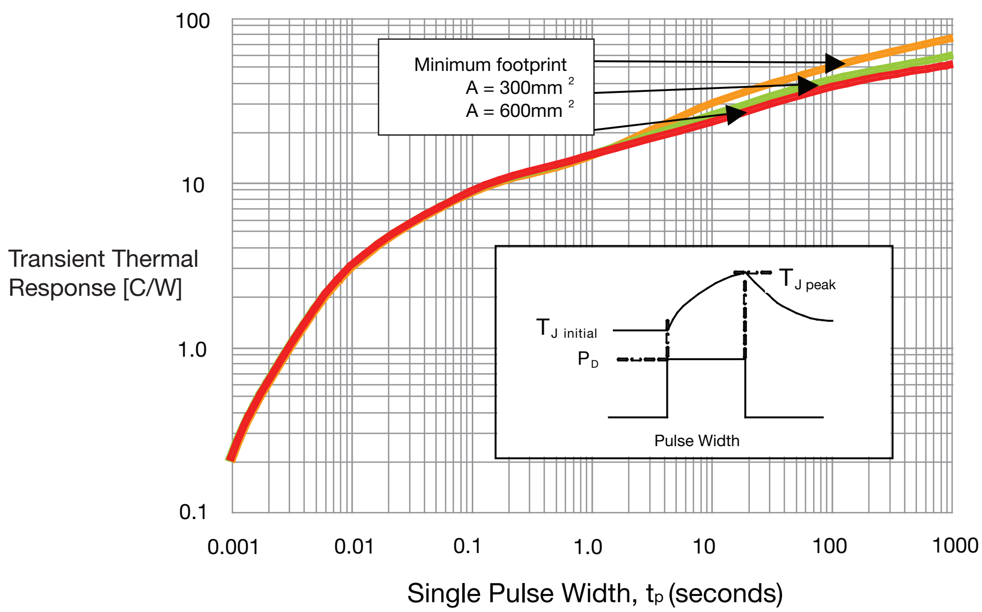
Transient thermal response is a device's or a system's thermal response to a step input of power. Note that the step input starts at zero power, steps to some amplitude, then remains at that amplitude forever. A transient thermal response curve is a plot of the junction temperature rise as a function of time. As such, the curve incorporates the thermal effects of a device's entire structure. Manufacturers usually create these curves empirically, but they can create them with models as well.

Each point on the curve shows the die's maximum temperature versus how long the power pulse has been present. Transient response curves can be referenced to case or ambient temperature.

It is important to note that the specific shape of the power pulse used in the characterization may not match the shape of the pulse of interest in the application. Therefore, it is important to remember what the thermal response curves represent and to use them accordingly.

Figure 9 shows the transient thermal response curve of a transistor in a 28-pin SOIC. The far right side of the curve shows the device's steady state thermal resistance. In this case the three possible values are for variously sized thermal pads.

Figure 9—Transient thermal response curve



At narrow pulse widths the thermal impedance is far less than its steady state value. For example, at one millisecond (ms) the thermal impedance is only 0.2ºC/W, about 100 times less than the steady state $R_{\Theta JA}$ value.

Near the center of the graph the three curves diverge, implying that for transients of less than one or two seconds in duration the device's heatsinking does not affect the peak temperature. Of course, this is true because the heat wave front begins to exit the package after those narrow pulse durations.

Part of the beauty of the transient thermal response curves is their ease of use. Replacing $R_{\Theta JA}$ with $Z_{\Theta JA}$ in the basic thermal equation we get:

$$T_{Jpk} = T_A + (P_D Z_{\Theta JA}) \qquad \text{(Eq. 8)}$$

Now let's assume that a system experiences a power transient with the following characteristics and ambient temperature:

Power pulse width, tp = 1ms

$P_D = 50W$

$T_A = 75ºC$

From Figure 9 we can estimate $Z_{\Theta JA}$ for a 1ms pulse width:

$Z_{\Theta JA}$ @ 1ms = 0.2ºC/W

then,

$\Delta T_{JApk} = (T_{Jpk} - T_A) = P_D Z_{\Theta JA}$

$T_{Jpk} = T_A + (P_D Z_{\Theta JA})$

$T_{Jpk} = 75ºC + (50W * 0.2ºC/W)$

$T_{Jpk} = 75ºC + 10ºC$

$T_{Jpk} = 85ºC$

To clarify understanding further and illustrate the importance of using such curves properly, consider the initial junction temperature of this example. It was not explicitly defined, but the use of the method sets its value. Transient response curves apply only to systems that have no initial power dissipation and that are thermally at equilibrium at time zero. Therefore, in this example the initial junction temperature must be the ambient temperature, or 75ºC.

Clever ways have been devised to use the transient response curves for repetitive pulses of the same magnitude, alternate pulse shapes and pulse trains of varying pulse widths and magnitudes. The basic concept used to achieve the broader usage is the "Superposition Principle." This principle states that for linear systems the net effect of several phenomena can be found by summing the individual effects of the several phenomena. References 1, 2 and 8 explain these techniques in detail.

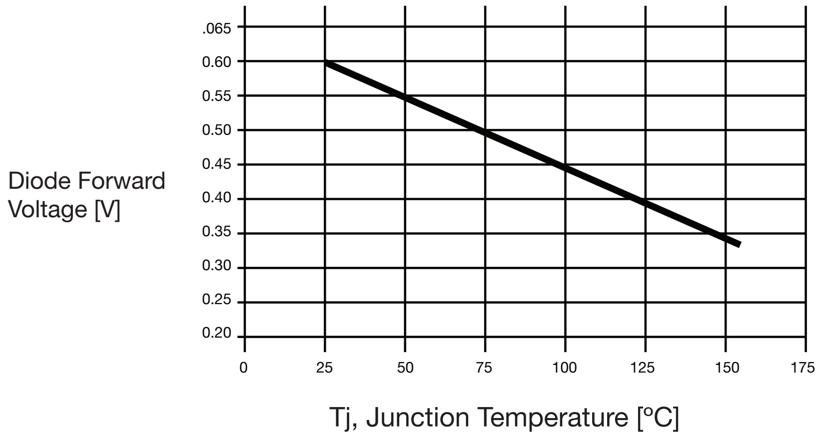
5 Ramifications of High Operating Temperature

Motivation to conduct thermal assessments arises from an understanding of how high operating temperature affects circuit assemblies and their reliability. Some of the effects are well known; others are much more subtle. Only a few can be briefly mentioned here.

One interesting effect relates to all P-N junctions on a die. A graph of diode forward voltage, Vf, as a function of temperature is shown in Figure 10. It contains no surprises, showing the well-known and well-behaved decrease in diode forward voltage with increasing temperature. Extrapolating the curve to an even higher temperature reveals that the forward voltage approaches 0V at about 325ºC.

The same relationship applies to the base-emitter junctions of a device's bipolar transistors, whether they are parasitic or not. The result is that at a very high temperature even modest base-emitter voltage can begin to turn on a transistor even though its base drive circuit is trying to keep the BJT off. A similar phenomenon occurs with MOSFETs because their gate-source threshold voltages fall with temperature. Consequently, if a severe electrical transient generates a hotspot, a BJT or MOSFET could reach a point of uncontrolled turn on. Its temperature may continue to increase, and permanent damage may ensue.

Figure 10—Diode forward voltage vs. operating temperature



High junction temperature has many other electrical and mechanical effects. Among them are:

- Leakage currents increase
- Gate oxides degrade more quickly
- Ionic impurities move more readily
- Mechanical stresses increase
- Diode forward voltage falls
- MOSFET on-resistance increases
- MOSFET threshold voltage falls
- Bipolar transistor switching speeds slows
- Bipolar transistor gains tend to fall
- Breakdown voltages tend to increase
- Transistor Safe Operating Areas decrease

Knowing some of the critical temperature milestones and thresholds is helpful in selecting the appropriate temperature ratings of other components and for conducting forensic activity.

-55ºC	Minimum semiconductor storage temperature
-40ºC	Minimum automotive operating temperature
60ºC	Metal surfaces are painfully hot
85ºC	Maximum temperature of many electrolytic capacitors
125ºC	Maximum operating temperature of many digital circuits
130ºC	Common FR4 circuit board maximum temperature rating
150ºC	Typical maximum junction temperature rating
165ºC to 185ºC	Typical power transistor over temperature shutdown
155ºC to 190ºC	Mold compound's glass transition temperature*
183ºC	Melting point of $Sn_{63}Pb_{37}$ solder (63% tin, 37% lead, eutectic)
188ºC	Melting point of $Sn_{60}Pb_{40}$ solder
217 to 220°C	Melting point of $Sn_{96.5}Ag_{3.0}Cu_{0.5}$ (96.5% tin, 3% silver, 0.5% copper)
280ºC	Typical melting point of die attach solder
~350ºC	Diode Vf approaches 0V
660ºC	Melting point of pure aluminum (wirebonds and metallization are often aluminum)
1400ºC	Melting point of silicon

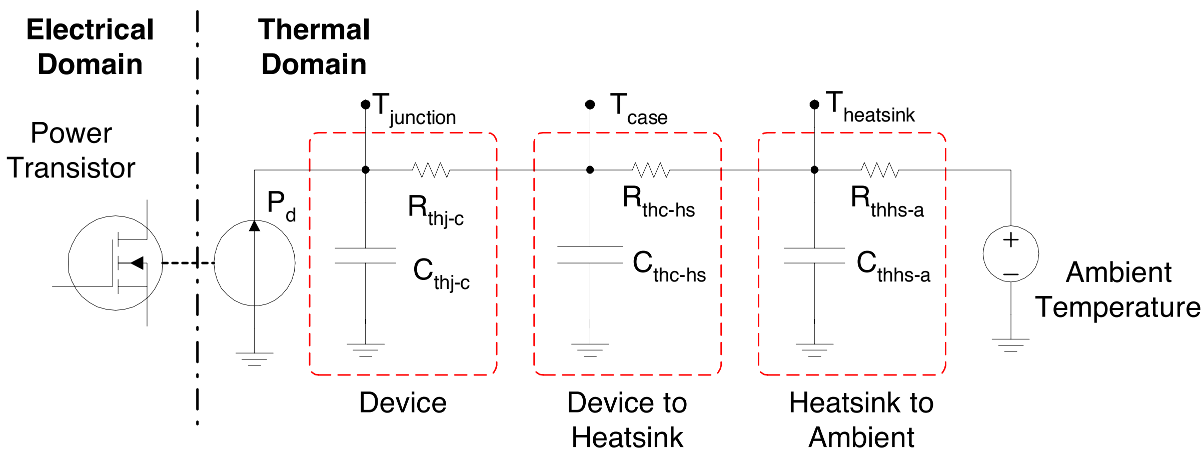
*Glass transition temperature is the mid-point of a temperature range in which a solid plastic material, which does not melt, softens and the coefficient of thermal expansion increases.

Figure 11 shows a common model used for a single power transistor and its heatsinking. The electrical behavior is accounted for by an electrical model on the far left side of the figure. Heat is transferred from the electrical to the thermal domain and is represented by a heat source, PD. The symbol for the electrical current source is reused in the thermal domain to denote the through variable. The heat source feeds successive RC networks that model the behavior of the actual mechanical assembly. Figure 11 shows three RC pairs, but a larger number could be used to more accurately model a complex system, or a smaller number could be used for a simple thermal network. The values of the R's and C's can be estimated using the system's material properties and physical dimensions, or they can be extracted from empirical tests.

the capacitor values are selected accordingly. The disadvantage of the parallel RC configuration is that the capacitance values do not directly relate to the system's physical features, that is, they cannot be calculated from the material's density, capacity and volume.

The model shown in Figure 11 is of a single transistor and consequently lacks any provision for thermal coupling between neighboring components. For circuits with multiple power dissipating elements the components in Figure 11 are replicated for each heat generating device, and thermal coupling resistors are placed between each combination of nodes. Obviously, the thermal schematic becomes more complex, but perhaps worse, the values of the new components must be determined, most commonly through empirical testing.

Figure 11—Electrical and Thermal Domain Circuits



For example, when the system is powered and is in steady state, the thermal resistances can easily be derived from the power dissipation and the temperatures at the three thermal nodes. Characterizing the transient response requires monitoring temperature response to a step input of power.

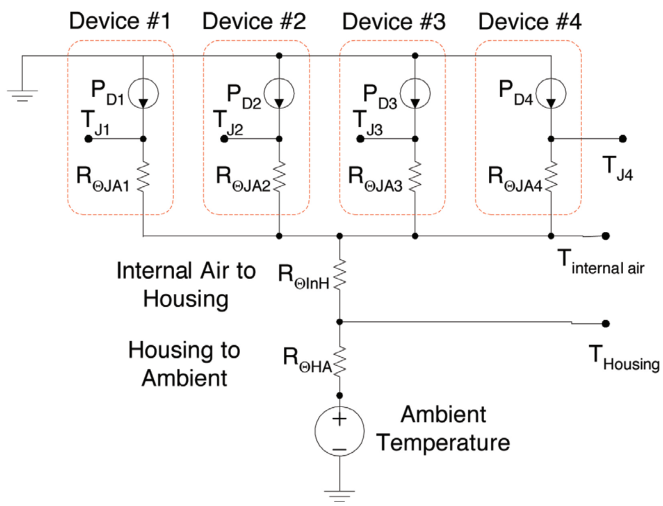
A good engineer will want to consider several aspects of this representation. First is the meaning of the reference, or ground, connection in the thermal domain. Since it is a node within the thermal domain, it is an across variable and must represent some reference temperature. There are two natural choices for this reference temperature: ambient temperature or absolute zero. A simple representation is to use absolute zero as the reference temperature then use a temperature source for ambient temperature.

The second consideration is how to terminate the thermal capacitances. The representation in Figure 11 connects the capacitor to the reference terminal. However, a circuit with an equivalent thermal response can be created with each of the capacitors in parallel with their respective thermal resistors. Some tools used to extract the RC thermal "ladder" more readily provide a circuit with the capacitors in parallel with the resistors. Either capacitor arrangement suffices if

The thermal circuit shown in Figure 12 is a popular way of roughly assessing multiple device behavior within a module. This method is not used for transient conditions, so Figure 12 does not include thermal capacitors. Each power dissipating device is treated independently of the others and is assigned a junction to ambient thermal resistance based on datasheet characterization and allotted circuit board area. The designer estimates the module's internal air temperature rise above ambient based on experience and adjusted to account for the module's size and its other thermally significant features. Finally, device junction temperatures are estimated from the device's $R_{\Theta JA}$, its power dissipation and the module's internal air temperature, which is the "ambient" temperature for the power device.

This method has the following three key weaknesses:

Figure 12—Popular thermal model for a module with multiple power devices

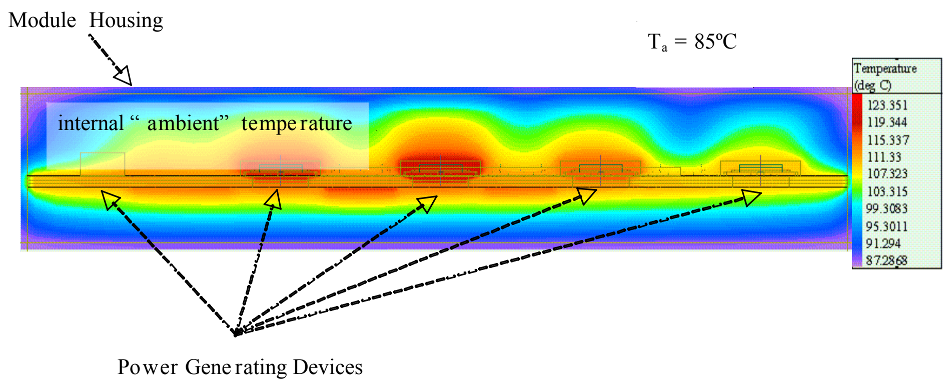


1. It does not account for thermal coupling between devices on the PCB. For this method devices affect one another only through their effect on the internal ambient temperature.
2. It assumes a constant internal air temperature even though we know "ambient" temperature within a module varies substantially with distance from the heat sources. Figure 13 illustrates the difficulty of selecting a single value for internal "ambient" temperature.
3. Conditions existing in a module differ considerably from the conditions used to specify the rated junction to ambient thermal resistance. The PCB's thermal characteristics differ and module's small volume constricts the flow of convective currents.

In spite of its clear drawbacks, this method is popular because it quickly yields a rough estimate of operating temperature.

Other approaches are used, but all have limitations because each inherently attempts to simplify a complex thermal circuit using a few

Figure 13—Thermal gradients within a module.



lumped components. One alternate approach accounts for thermal coupling between devices and is practical for systems with up to four or five power devices. The improved accuracy comes at the cost of additional empirical characterization and the need to solve several or even many simultaneous equations. As the number of power components increases, this rapidly becomes more difficult.

The first step of this method is to measure the junction to ambient thermal resistance of each device when all other devices are not generating power. Such a direct measurement gives the designer an accurate value for the thermal resistance of that device in that application. As a check, the calculated value should be compared to the thermal resistance specifications.

The next step is to determine how each device heats its neighbors, that is, the thermal coupling coefficients between devices. Use either a thermal mock-up or a module prototype to determine these thermal coupling factors. You can determine the coupling factors by powering only a single device and measuring the temperature rise at every other critical device. The coupling coefficient is the ratio of the induced temperature rise in the unpowered device and temperature rise in the powered device caused by self heating.

After taking the first round of measurements, individually power all other devices in sequence and measure the temperature increases each device induces in all other devices. Once these thermal coupling coefficients are known the junction temperature of each device can be estimated by solving simultaneous equations. Their equations can be represented in matrix form as:

$$\begin{vmatrix} T_{J1} \\ T_{J2} \\ T_{J3} \\ T_{J4} \end{vmatrix} = \begin{vmatrix} c_{11} & c_{21} & c_{31} & c_{41} \\ c_{12} & c_{22} & c_{32} & c_{42} \\ c_{13} & c_{23} & c_{33} & c_{43} \\ c_{14} & c_{24} & c_{34} & c_{44} \end{vmatrix} \times \begin{vmatrix} P_1 R_{\_JA1} \\ P_2 R_{\_JA2} \\ P_3 R_{\_JA3} \\ P_4 R_{\_JA4} \end{vmatrix} + \begin{vmatrix} T_A \\ T_A \\ T_A \\ T_A \end{vmatrix}$$

where c_{mn} is the coupling coefficient between Device m and Device n, $R_{\Theta JCm}$ is the junction to ambient thermal resistance of Device m, and P_m is the power dissipated by Device m. By the way, do not assume that c_{mn} is equal to c_{nm}.

For systems with many power dissipating sources the characterizations and calculations become unmanageable. This is when commercially available thermal modeling software tools can be used.

7.1. Uses of Thermal Modeling Software

A designer's primary thermal concern is that his module must economically meet all the system's requirements under worst case

7 Thermal Modeling Software

loading and operating conditions. Given there are many, many ways to implement a system, the designer needs an efficient way to search for the workable solutions among the vast number of possible ones. Furthermore, the task also requires converging on the final design as quickly and efficiently as possible. Cost and time constraints prohibit searching for the optimum design by redesigning and testing many successive hardware variations. You may be restricted to just a few cycles of building, testing and modifying a module because respinning PCBs takes time, and modifying the module's housing or connector is particularly expensive. Thermal analysis software can speed design by providing critical guidance during the search process.

If you are designing a system that has no predecessor, you will immediately face basic questions, such as:

- How much power will my system dissipate?
- How much power can my system dissipate without overheating?
- What is the system's primary thermal path?
- What are the most effective means of improving that path?
- How much will one element heat its neighbor? …and so on

Three analysis tools can be used in combination to answer these and other questions:

1. Analysis using manufacturers' thermal ratings and characterizations
2. Empirical testing of a prototype or of a thermal mock-up
3. Thermal modeling

Before using a set of thermal modeling tools, it's appropriate to consider the purpose of the modeling, the characterization data available to support those models and what a particular software tool can and cannot provide. These are some of the best uses of thermal analysis software:

Provide tradeoff assessments before any hardware is built

A model of a proposed implementation is a fast and low-cost way of assessing if that implementation can potentially meet the system's requirements. However, you should expect that a first pass thermal model will likely require refinements or even major revisions after you compare the model's simulation results to empirical test results of actual hardware.

Uncover poorly understood thermal phenomena

After you decide on the first pass hardware, based on an initial thermal model, the next steps are to build the hardware, characterize it and compare empirical test results to the model's predictions. Implicit in this discovery process is that the designer must calibrate and validate the model by empirically testing hardware.

More than likely there will be mismatches between the empirical and modeled results. These incongruities identify thermal behaviors that were not modeled properly, most likely because they were poorly understood, thought to be unimportant or simply overlooked. Perhaps the best use of modeling is to identify critical module characteristics that were misrepresented in the model and to use that information to improve your understanding of the module.

A calibrated thermal model speeds development

Once a thermal model is calibrated it becomes a powerful tool to explore potential variations in the next layout iteration. Altering the model and rerunning simulations is usually much faster and less expensive than modifying the layout and retesting the hardware.

Once you create a validated thermal model it can, of course, be used as a starting point for future modules of similar design.

A model can be used to assess test conditions that are difficult to create

Testing a module under some conditions is difficult or impractical. In these cases a calibrated thermal model can be used instead.

Testing under worst case conditions is a good example of a set of system conditions that are difficult to create. Let's assume that you would like to test the system with power transistors that have worst case on resistances. You are not likely to find such devices for empirical testing, but modifying the transistor's power dissipation in the model is easy. Or, you may have hardware limitations, such as oven volume or temperature range, that prohibit certain tests. These could be explored in the simulated domain instead.

Thermal models accurately simulate behavior of simple structures

A thermal model of a simple structure can be quite accurate because we can precisely describe simple structures mathematically. This strength of thermal modeling gives it a special advantage for simple structures that are difficult to empirically test, such as a power die on a leadframe. Empirical testing is not likely to help map junction temperature variations across a die, especially during transients. A calibrated model is a handy tool for these situations.

Thermal models provide a means to estimate a system's response to power transients

A system's worst case operating conditions are often transient, so dynamic conditions often dictate the system's required capability. It's difficult enough to envision how heat flows in a system under steady state conditions let alone estimating how temperatures change during a transient condition. Models can provide badly needed guidance in these situations. Some allow you to create movies of the temperature during transients, providing the designer with a more intuitive sense of how the system is performing.

7.2. Thermal Modeling Software Options

There are quite a few commercially available thermal modeling software packages. Each package claims its niche. Whether you are selecting a package or using one that your company already has, it is good to understand how they differ. Some of the differentiating features are:

- Cost, including hardware and maintenance fees
- Simulation speed
- Training required for competency
- Ability to model all three modes of heat transfer, which for convection requires the ability to model fluid flow
- Ability to model responses to time varying power waveforms
- Ability to import files from other CAD packages
- Method of managing boundary conditions
- Ability to use a multi-level nested mesh
- Ability to link thermal models to models in other domains (e.g., electrical models)
- Inclusion of a software library that contains common thermal elements, such as heatsinks, enclosures, PCBs, etc.
- Ability to view and export a simulation's results
- Customer support, including technical literature
- Numerical method used to solve the governing mathematical equations

A program's numerical method, the last item in the above list, is the most fundamental feature of each program. The numerical method is the means by which the software resolves the governing mathematical equations.

Numerical methods used in thermal analysis software include the Boundary Element Method, Finite Difference Method, Finite Element Method and Finite Volume Method. The latter is the method most often used in computational fluid dynamics (CFD) software.

The particular numerical method a program uses makes it more or less suitable for specific modeling tasks. The most obvious example is CFD software. Like all viable thermal analysis software, it accounts for conduction and radiation. But CFD also predicts fluid flow, which is necessary to model convection. Therefore, if convection is a primary transport method in your systems, you will likely require CFD software.

ANSYS is one well known CFD thermal analysis software supplier that offers CFX, Fluent, Iceboard and Icepak. Flomerics is another well respected vendor and provides Flowtherm, which is the simulation software used to create the image in Figure 13. CFD programs provide the ability to view and export images of fluid speed and direction. This feature helps to clearly illustrate the size and effectiveness of thermal plumes, which are likely to form above hot surfaces.

When convection is not a significant thermal transport mechanism, a program capable of modeling fluid flow is not necessary. An example of such a system is a semiconductor package mounted to a heatsink that is at a fixed or known temperature. A software package optimized for conductivity might simulate faster or give more accurate results, such as one using the Boundary Element Method. Instead of breaking the modeled volume into a mesh of much smaller units, the BEM creates a mesh on the surface of a solid. From the conditions at the surface, it predicts the temperature and heat flux within the solid. Because the BEM does not discretize the volume, it does not suffer from the problems associated with having a mesh size that is too small (excessively long simulation times) or too large (reduced accuracy). For simple structures, such as a die in a package, the BEM is a fast and accurate numerical method. Freescale engineers have successfully used Rebeca 3D, a BEM package supplied by Epsilon Ingénierie, to evaluate hotspot temperature of power die in a multi-die package.

Even the most sophisticated thermal analysis software package is not a panacea. Obviously, the quality of its predictions depends on the model's inputs, such as the system's physical dimensions and material properties. The results also improve with the detail included in the model, but the simulation times increase accordingly. Therefore, regardless of which modeling software is used, to obtain the most value from a simulation you should carefully discuss the system's pertinent features with the engineer creating the model, including: the mechanical features of the system; heat source sizes and locations; potential thermal paths; all material characteristics; system orientation; physical boundary to be modeled, etc. The engineer creating the model should carefully explain the simplifying assumptions he/she plans to make.

Appendix B contains a table of thermal properties of materials used in typical semiconductor packages.

8 Empirical Analysis Techniques

The tools used for empirical thermal analysis are fairly well known.

The most common tool, of course, is the thermocouple. A few guidelines to their use are:

1. Make sure your thermocouple type (J, K, T or E) matches your meter setting.
2. Use small gauge thermocouple wires. This reduces the heatsinking effect the leads have on the device under test.
3. Monitor as many points as practical to improve your overall understanding of the circuit and to enhance your chance of detecting unexpected hot spots.
4. Place probes at nodes as close as practical to the die of interest. This measurement location need not be in the primary thermal path. For instance, the temperature at the top of the package or at an exposed tab may be very close to the die temperature even though the measurement location is not in the primary thermal path.

Infrared scanning is a very helpful technique because it provides information about the entire scanned area. Discovering unexpected hot spots, such as undersized PCB traces or connector pins, with an infrared scan is not uncommon. This can be very helpful during prototyping where assembly problems might otherwise go unnoticed. A disadvantage of thermal imaging is that the camera must have access to the device or PCB under test. Opening a module to provide such access significantly alters the behavior you are trying to measure. Handheld, infrared, contactless thermometers are inexpensive and easy-to-use tools for taking spot measurements.

It's possible to measure a device's junction temperature by monitoring a temperature sensitive parameter (TSP) of one of its components. A diode's forward voltage, Vf, is one the most commonly used TSPs, and diodes may be readily accessible as ESD structures on a logic pin, for example. The body diode of a power MOSFET is another often used component, but using that diode requires reversing the current in the MOSFET, which requires a bit of circuit gymnastics. Over temperature shutdown (if available), MOSFET on-resistance and MOSFET breakdown voltage are also options. Using a TSP requires establishing the TSP's variation over temperature, which must be done at near zero power.

When making thermal resistance measurements, you should try to use power levels that will generate easily measurable temperature increases. A larger junction to ambient temperature differential increases the quantity you are attempting to measure (temperature rise) relative to any potential measurement errors in the system.

A common system requirement is that a module must operate at a certain ambient temperature in still air. These conditions sound simple enough to create, but the high test temperature will require an oven and an oven often uses circulating air to control the temperature. Its fan ensures the oven's air is not still. To circumvent this problem you can place a box in the oven and place the module in that box. Of course, the box reduces the air speed around the module. With this arrangement the oven temperature can be adjusted to attain the specified "ambient" temperature in the box.

If you are designing a system that has a predecessor, use data from that module as a starting point. If the system has no predecessor, then consider building a thermal mock-up that will mimic the final module's behavior. Such a mock-up might have little or no electrical similarity to the intended module, but it should have mechanical and thermal similarity. Because an electrical circuit does not have to be built, programmed and debugged, you might be able to create a thermal prototype of your module very quickly to assess total module power budget, thermal coupling, affects in changes to the primary thermal path, etc.

Finally, plan to use empirical testing in conjunction with thermal resistance ratings and thermal models to enhance your understanding of the system.

9 Optimizing the Thermal Environment

There are many ways to reduce the operating temperature of semiconductor devices. Some of the techniques add little or no additional cost to the module. Below are some suggestions:

Reduce the module's or IC's thermal load.

The most direct way to deal with excessive heat is to not generate it in the first place. Portions of the circuit may be turned off. Load shedding (if allowed), careful fault management, using oversized power transistors or using ICs with power saving features are some of the ways to cut a module's total dissipation. Carefully defining the module's worst case operating conditions is sometimes the most effective way to reduce power dissipation.

Reduce thermal impedance in the IC's immediate vicinity.

Semiconductor die are quite small compared to the size of a typical module, and this results in very high heat flux in the die, the package and its immediate vicinity. Therefore, thermal resistance encountered early in the thermal path causes a large temperature gradient. That is why temperature often falls rapidly as you move from the die into its package and then into rest of the system. The most effective place to focus resources to reduce thermal resistance is where the thermal gradient is highest. So, be especially mindful of how the package is attached to the PCB or heatsink and how thermal energy is transferred and spread in that area. Spreading the heat at the beginning of the thermal path not only reduces the thermal resistance near the IC, but it also provides a broader area to further disseminate the heat. Reducing the thermal impedance close to the die and package is mandatory for good thermal performance.

Use a continuous low impedance path from the IC to ambient.

Around the IC, provide an uninterrupted copper path to a large pad to radiate heat, a heatsink, the module's harness, etc. Any small break in low impedance material is highly detrimental. Provide redundant thermal paths where possible.

Increase the surface area from which the heat exits the module.

Ultimately, some surface will radiate the module's heat or disperse it by convection. Use all available features, such as the harness as well as the housing. The utility of the harness depends on the number and gauges of its wires, its insulation, its own ohmic losses and how well heat can flow from the PCB through the connector and into the harness.

Separate heat generating components.

Place heat generating components as far apart as possible to reduce thermal coupling effects. The thermal gradient is high near a power dissipating device, so even small amounts of separation help reduce thermal coupling.

Use thick copper cladding, if allowable.

The cross sectional area of a trace is quite small and can constrict heat flow. Using heavier copper cladding reduces this effect. However, if fine pitch ICs are used on the board, using heavier copper cladding may violate manufacturing guidelines.

Beware of PCB trace and connector pin heating.

Modern power electronics devices can have very low on-resistances. It's quite possible that the PCB traces and connector pins that feed current to these devices contribute more ohmic losses to the system than the power transistors do. Such heating may be avoidable if traces are upsized. Reducing trace ohmic losses may be the least expensive way to reduce the module's total power dissipation. Trace width calculators, which also predict trace temperature rise, are readily available on the internet.

Consider the effects of PCB and module orientation.

Heat convection is more efficient for a vertically mounted board. Remember that components above heat producing devices run hotter than those below.

If the board is to be horizontally mounted, place heat generating devices on the PCB's topside, if possible. A thermal plume forms more readily on a board's topside and it helps disperse heat.

Take advantage of thermal capacitance, if possible.

Worst case conditions are often briefer than the module's thermal time constant. Upon a change in operating conditions, a module can easily take more than 10 minutes to stabilize thermally. The system may be able to store the energy from the worst case conditions in the module's thermal capacitance. Heat sinks, heavy copper and multi-layered boards all add to the module's thermal capacitance.

Remember, too, that even when a device is mounted to a worst case board, the device itself has some ability to absorb energy. If a device has fast fault detection circuitry, it may be able to absorb the energy and manage the fault without harm to the device, the PCB or the load.

Expect surprises.

Because we have a limited innate ability to sense thermal phenomena, we lack an intuitive feel for how thermal systems behave. This makes it advisable to monitor temperature at many points on a PCB or, better yet, photograph the module, its PCB, and its harness with an infrared camera. Any unexpected temperatures you find point you to aspects of the thermal circuit that you do not completely understand. Finding these surprises provides valuable clues that can lead to a better understanding of the module's thermal behavior.

10 Appendices

10.1. Appendix A—List of JESD51 Series Publications

JESD51	"Methodology for the Thermal Measurement of Component Packages (Single Semiconductor Device)"
JESD51-1	"Integrated Circuit Thermal Measurement Method—Electrical Test Method (Single Semiconductor Device)"
JESD51-2	"Integrated Circuit Thermal Test Method Environmental Conditions—Natural Convection (Still Air)"
JESD51-3	"Low Effective Thermal Conductivity Test Board for Leaded Surface Mount Packages"
JESD51-4	"Thermal Test Chip Guideline (Wire Bond Type Chip)"
JESD51-5	"Extension of Thermal Test Board Standards for Packages with Direct Thermal Attachment Mechanisms"
JESD51-6	"Integrated Circuit Thermal Test Method Environmental Conditions—Forced Convection (Moving Air) "
JESD51-7	"High Effective Thermal Conductivity Test Board for Leaded Surface Mount Packages"
JESD51-8	"Integrated Circuit Thermal Test Method Environmental Conditions—Junction-to-Board"
JESD51-9	"Test Boards for Area Array Surface Mount Package Thermal Measurements"
JESD51-10	"Test Boards for Through-Hole Perimeter Leaded Package Thermal Measurements"
JEDEC51-12	"Guidelines for Reporting and Using Electronic Package Thermal Information"

10.2. Appendix B—Thermal Properties of Common Semiconductor Packaging Materials

Material	Conductivity K	Relative Conductivity	Thermal Capacity CP	Density	Volumetric Heat Capacity	Relative Volumetric Heat Capacity
	(W/m K)	–	(J/kg K)	(kg/m3)	(J/K m3)	–
Epoxy Mold Compound	0.72	0.00200	794	2020	1603880	0.4748
Silicon (at 25C)	148	0.41111	712	2328.9	1658177	0.4908
SnPb Solder	50	0.13889	150	8500	1275000	0.3774
Silver Filled Die Attach	2.09	0.00581	714	3560	2541840	0.7524
CU Lead Frame	360	1.00000	380	8890	3378200	1.0000
FR-4	0.35	0.00097	878.6	1938	1702727	0.5040
Air	0.03	0.00008	1007	1.16	1170	0.0003

Values may vary with specific type of material, temperature

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