Tackle Thermal Design At the System Level

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A practical approach to optimizing thermal performance of power systems begins with an understanding of how semiconductor manufacturers characterize the performance of their devices.

Designing a cost-competitive electronic system requires careful consideration of the thermal domain as well as the electrical domain, especially where power is involved. Overdesigning the system adds unnecessary cost and weight, but underdesigning 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 microcontroller units.

Same Goal, Different Perspectives

While the semiconductor supplier and system designer may have the same goal — a successful end product — when it comes to thermal analysis, they are not usually on the same page. Semiconductor manufacturers know the thermal aspects from the semiconductor's perspective. In most cases, semiconductor users have their techniques to evaluate the entire system. However, when the two interface, there can be problems.

One reason may be an educational perspective: The thermal aspect is in the mechanical engineer's realm. For a successful module design, many electrical engineers find themselves handling packaging and thermal aspects — areas in which they may not have the appropriate or sufficient background to address. Without a little additional insight, they may have a painful and unnecessary learning experience.

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	$R_{\theta JC}$	—	1.2	°C/W
Junction to lead	$R_{\theta JL}$	18	—	
Junction to ambient	$R_{\theta JA}$	70	71	

Table. *Typical thermal resistance specifications.*

While impossible to address in a single technical article, a brief discussion of a few key areas can get the system designer on track and headed in the right direction.[1] But first, consider a couple of system examples that further demonstrate the need for understanding thermal design.

For automotive systems, reducing the weight and size of everything has become a high priority. As a result, for the electronic modules, plastic has become a common housing material instead of the cast aluminum housing with a good-sized aluminum heatsink that many systems used previously.

For instance, a lighting control module built using advanced power ICs with highly efficient power switches conducts 55 A, yet is housed in a plastic case with no heatsink. The only heatsinking is that provided by the module's pc board. While not unusual, this could not have been possible just a few years ago. However, a complete thermal analysis and evaluation was required.

In another case, a module initially designed with relays was converted to use the latest analog and mixed-signal intelligent power devices to control lighting. To handle up to 80 A in a plastic case without any heatsink, the copper wiring harness was used to remove heat from the module. In this case, the module designer had to confront thermal issues that were not present in the relay-based design.

Start with the Data Sheet

Looking at the device data sheet sounds simple, but it can reveal as many as five or six different thermal ratings for some ICs. To choose the right one, the designer should use the value for the primary thermal path for heat removal. The table shows three thermal resistance (R_θ) parameters for two different packages. The two packages require different techniques to measure the temperature. Fig. 1 shows the required approach for each.

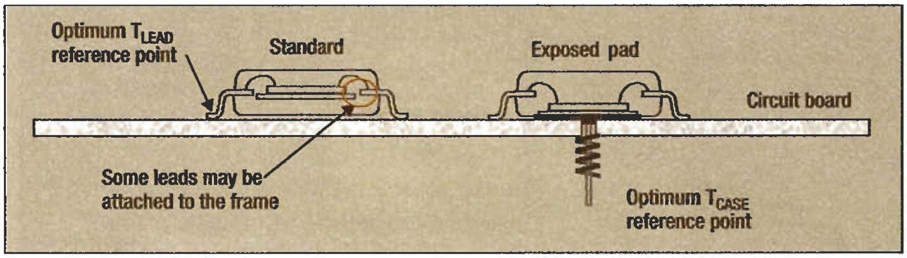


Fig. 1. *Package construction determines the optimum location for measuring temperature on an IC as depicted here for a standard SOIC package (a) and an SOIC with a die attach pad (b).*

It turns out that temperature measurements are not easy, especially as the IC package size shrinks. To estimate the junction temperature based on the temperature at the top of the package, JEDEC has standardized the terms for psi-junction to top of package (Ψ_{JT}) and psi-junction to board (Ψ_{JB}). These are thermal characterization parameters, not true thermal resistances. However, psi is a complementary parameter that can be used in parallel with the traditional ratings.

Someday systems engineers may use thermal characterization involving psi frequently, but today suppliers do not consistently provide information on psi on new product data sheets, and existing data sheets rarely have this information. The tried-and-true R-theta approach is one where the required data is available, and the designer needs to use several tools and methods to support his or her evaluation.

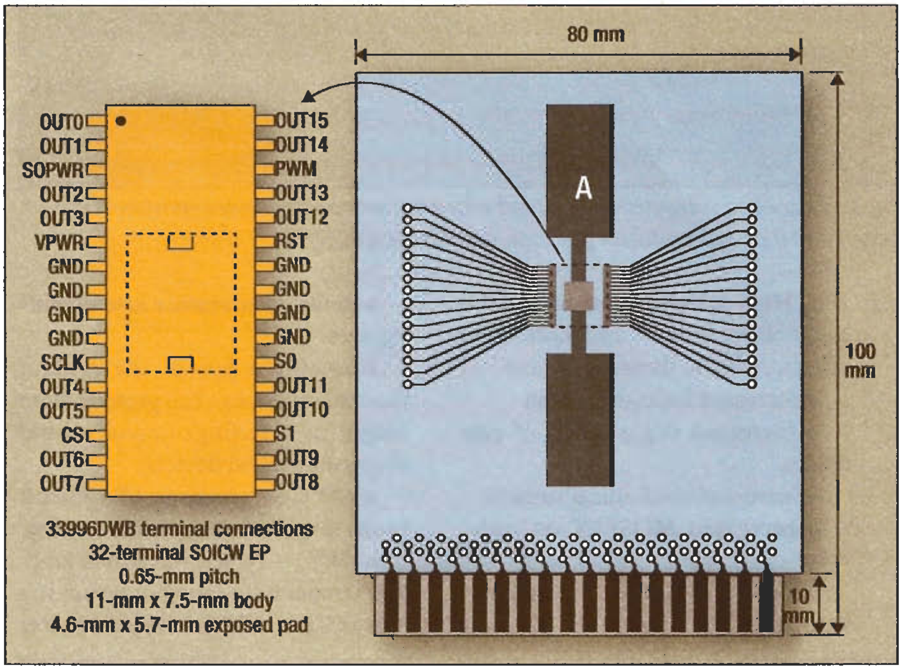


Fig. 2. *Thermal resistance test board with a dedicated thermal pad versus a worst-case JEDEC board. In contrast to the large extended copper area indicated by the A, the JEDEC worst-case characterization for $R_{\theta JA}$ would be within the dotted square area.*

Without additional thermal consideration, a manufacturer's data sheet showing 71°C/W, a worst-case JEDEC $R_{\theta JA}$ rating, would not be used in many applications. However, with a little additional copper on the board, as shown in Fig. 2, and by using copper in the wiring harness, the application could provide a 50°C/W rating and be quite acceptable. Fig. 3 shows data frequently found on a power IC data sheet indicating how additional copper reduces the thermal resistance.

Semiconductor suppliers cannot provide a thermal resistance value for the end application, because the application stack-up impacts and determines the thermal path, as shown in Fig. 4. A large portion of the thermal resistance is in the thermal interface itself. Simply routing the heat out of the back of a package, such as a PQFN, to a minimal pad size results in quite high thermal resistance. With a larger pad or vias or even a heatsink on the back of the board, the thermal resistance can be reduced from 70°C/W to as low as 5°C/W.

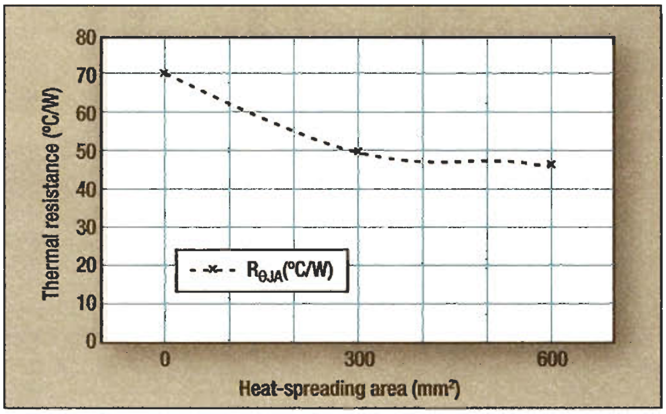


Fig. 3. *The addition of dedicated copper thermal pads predictably reduces the thermal resistance.*

High Temperatures

The main goal in thermal analysis is avoiding problems from excessive temperatures, including thermal runaway where the junction temperature increases until the device

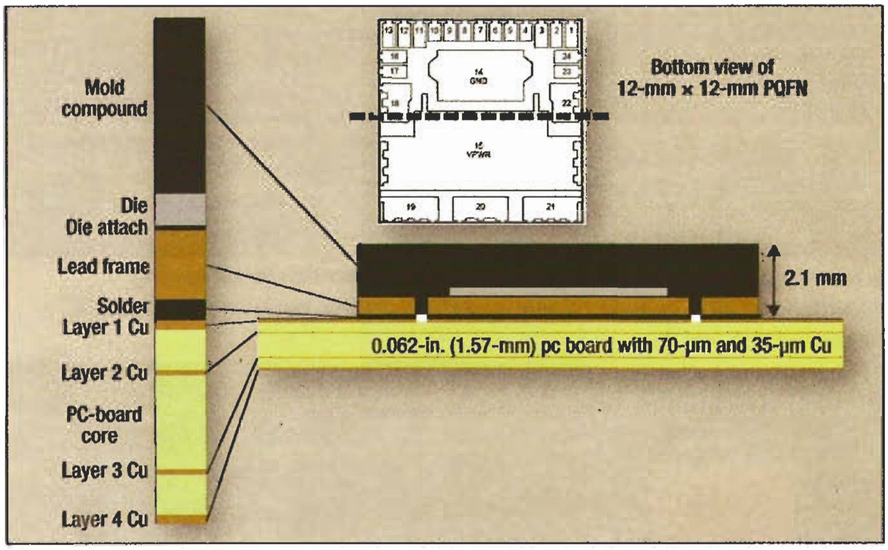


Fig. 4. *The cooling subsystem associated with a semiconductor device consists of the pc board and the semiconductor package, in this case a PQFN.*

fails. High junction temperature has many other electrical and mechanical effects. A few of these effects are:

- Increased leakage currents
- Increased degradation of gate oxides
- Increased mechanical stresses
- Increased MOSFET on-resistance
- Reduced MOSFET threshold voltage
- Reduced transistor safe operating area.

Knowing a few of the critical thermal milestones can provide more insight into selecting components and diagnosing failed devices:

- 130°C — common FR4 circuit board maximum temperature rating
- 150°C — typical maximum junction temperature rating of power ICs
- 165°C to 185°C — typical power IC and power transistor overtemperature shutdown
- 155°C to 190°C — mold compound's glass transition temperature
- 183°C — melting point of $Sn_{63}Pb_{37}$ solder (63% tin, 37% lead, standard eutectic solder)
- 217°C to 220°C — melting point of $Sn_{96.5}Ag_{3.0}Cu_{0.5}$ (96.5% tin, 3% silver, 0.5% copper, high-temperature solder)
- 280°C — typical melting point of die attach solder
- 660°C — melting point of pure aluminum (metallization and wirebonds are often aluminum)
- 1400°C — melting point of silicon.

To investigate the thermal aspects of a particular system, three analysis tools can be used in combination to answer questions about temperatures: empirical testing of a prototype or of a thermal mock-up; analysis using manufacturers' thermal ratings and characterizations; and thermal modeling.

Characterizing Systems

In the product development schedule, the use of empirical testing to supplement the data from thermal resistance ratings and thermal models enhances the understanding of the system. Common tools for empirical testing include measurements with thermocouples, infrared scanning and measuring a device's junction temperature by monitoring a temperature-sensitive parameter (TSP) of one of its components. Following are a few tips for each.

For thermocouple measurements, using the smallest gauge wire possible reduces the heatsinking effect of the leads. Monitoring as many points as practical improves the overall understanding of the circuit and enhances the chance of detecting unexpected hot spots.

Infrared scanning is very helpful because it provides information about the entire scanned area. Discovering unexpected hot spots, such as undersized pc-board traces or connector pins, with an infrared scan is not uncommon.

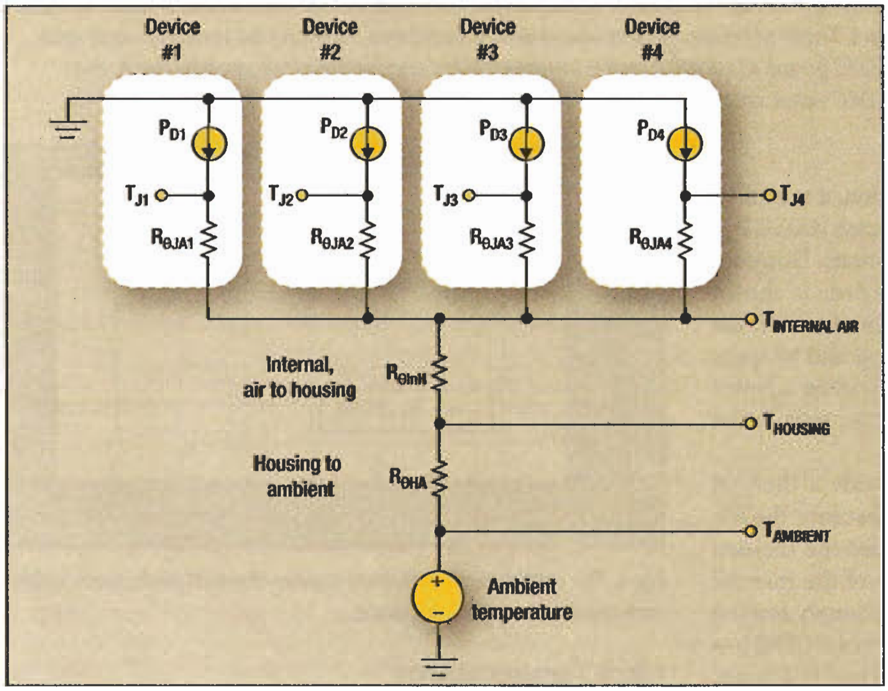


Fig. 5. *This popular thermal model for multiple power devices provides a rough assessment of thermal performance since it does not include thermal capacitance and ignores on-board thermal coupling.*

A diode's forward voltage is one of the most commonly used TSPs, and diodes may be readily accessible as electrostatic-discharge structures on a logic pin, for example. Using a TSP requires establishing the TSP's variation over temperature, which must be done at near-zero power.

A thermal mock-up that mimics the final module's behavior with similar mechanical and thermal characteristics, but little or no electrical similarity, can provide a quick evaluation tool to assess the total module power budget, thermal coupling, effects in changes to the primary thermal path, and more.

Models and Ratings

Several simple thermal models use the supplier's thermal ratings and the actual application interface. However, all have limitations because each inherently attempts to simplify a complex thermal circuit using a few lumped components.

To model transient conditions, the thermal circuit needs to include capacitance as well as the thermal resistance values for junction to case, case to heatsink and heatsink to ambient. 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.

For example, when the system is powered and 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. As the number of power devices increases, this approach becomes quite complex.

For a module with multiple power devices, a model that accounts for each device's power dissipation, junction temperature and thermal resistance, but not thermal capacitance, is quite popular. As shown in Fig. 5, each device is treated independently with a common internal air temperature separated from the housing temperature by a single internal air-to-housing thermal resistance and from the ambient temperature by a housing to ambient thermal resistance.

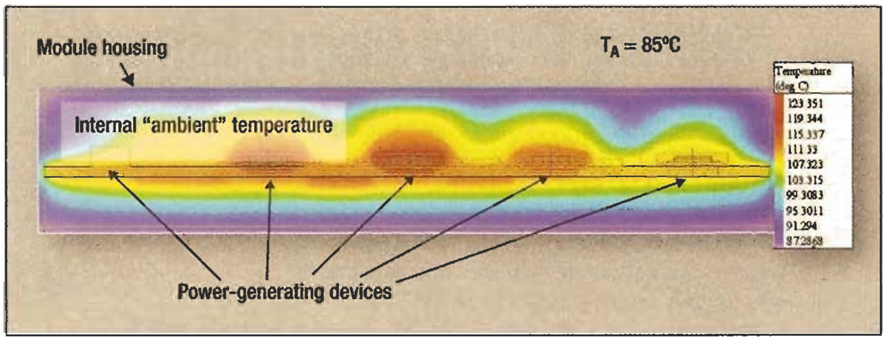
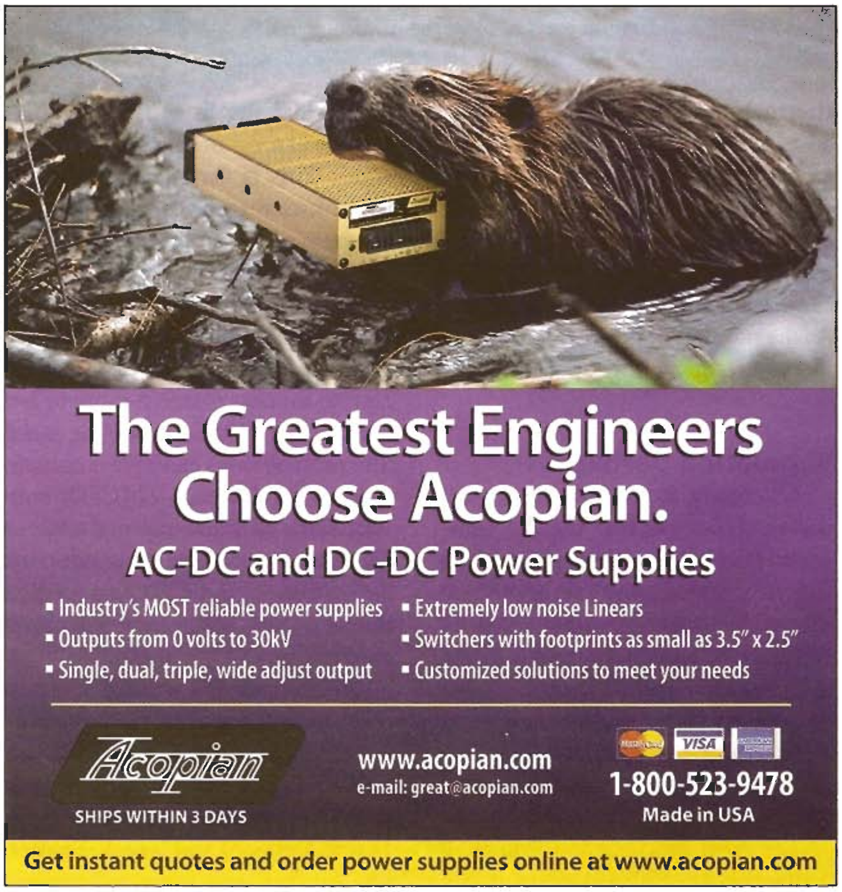


Fig. 6. *Thermal gradients within a module demonstrate the temperature variations that make it difficult to assume a single internal ambient.*

The designer estimates the module's internal air temperature rise above ambient based on experience and adjusts to account for the module's size as well as 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.

Fig. 6, which depicts a design that has been simulated using Flomerics' FLOTHERM simulation software, illustrates the compromise that results from using a single internal ambient temperature. In this example, external temperature is 85°C and the maximum temperature is 123°C, but this temperature occurs on only one of five power devices.

Yet another approach accounts for



Selecting Thermal Analysis Software

Designers must carefully evaluate what a particular thermal analysis software program can and cannot do. These are some of the best uses:

- Provide tradeoff assessments before any hardware is built
- Uncover poorly understood thermal phenomena
- Speed development
- Assess test conditions that are difficult to create
- Accurately simulate behavior of simple structures
- Provide a means to estimate a system's response to power transients.

There are quite a few commercially available thermal modeling software packages. Each package claims its niche, and it is important to understand how they differ. Some of the differentiating features are[2]:

- Cost, including hardware and maintenance fees
- Training required for competency
- Simulation speed
- 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 multilevel uniform and nonuniform-nested mesh (ability to create a body-shaped mesh is a plus)
- Ability to link thermal models to models in other domains
- Inclusion of a software library that contains common thermal elements such as heatsinks, heat pipes, enclosures and pc boards
- Ability to view/export simulation results in a generally accepted format
- Customer support, including technical literature
- Numerical method used to solve the governing mathematical equations.

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.

Simulation Software

Ultimately, the complexity of thermal modeling can lead users to commercially available thermal modeling software. 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 program can and cannot provide (see the sidebar above).

The most fundamental feature of a thermal analysis program is the numerical method used to solve the governing mathematical equations. This is the means by which the software resolves the governing mathematical equations, including the momentum and energy equations, coupled with the continuity (conservation-of-mass) equation.

The particular numerical method a program uses makes it more or less suitable for specific modeling tasks. The most obvious example is computational fluid dynamics (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.

If convection is a primary transport method in the system, CFD software is probably required. ANSYS is one well-known CFD thermal analysis software supplier and offers CFX, Fluent, Iceboard and Icepak. Flomerics, another well-respected vendor, provides FLOTHERM. CFD programs provide the ability to view and export images of a fluid's speed and direction. This feature helps to clearly illustrate the size and effectiveness of thermal plumes, which are likely to form above hot surfaces in the presence of natural convection.

Optimize the Environment

Reducing the operating temperature of semiconductor devices involves several techniques, many of which add little or no cost to the end module. Some possibilities include reducing the module's or IC's thermal load, reducing thermal impedance in the IC's immediate vicinity or using a continuous low-impedance path from the IC to ambient.

It is also possible to increase the surface area from which the heat exits the module or to use thick copper cladding, if allowable. Another option is to avoid the heating of pc-board traces and connectors. Also, consider the effects of pc-board and module orientation and, if possible, take advantage of thermal capacitance.

No matter which approaches or how many techniques are used, expect surprises. Monitoring the temperature at many points on a pc board or photographing the module and its harness with an infrared camera may reveal unexpected temperatures and misunderstood aspects of the thermal circuit. Finding these surprises provides valuable clues that can lead to a better understanding of the module's thermal behavior and, in the end, a more reliable product.

References

1. The equations used to calculate thermal resistance and impedance are usually found on the data sheet. For a more detailed explanation of the calculations, refer to Freescale's white paper online by searching *BASIC THERMWP* at www.freescale.com.
2. "Important Questions to Ask When Evaluating Thermal Analysis Software for Electronics," Stokes Research Institute, www.stokes.ie/pdf/Questionnaire.pdf.

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