Section One: Definitions and Basic Principles

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 provides 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.

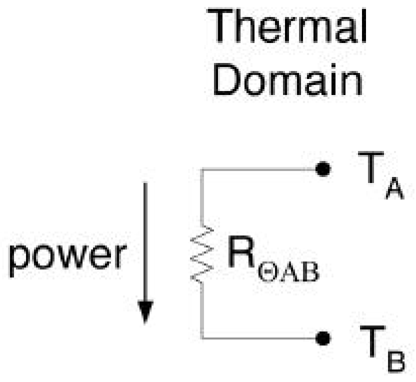
Definitions

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:

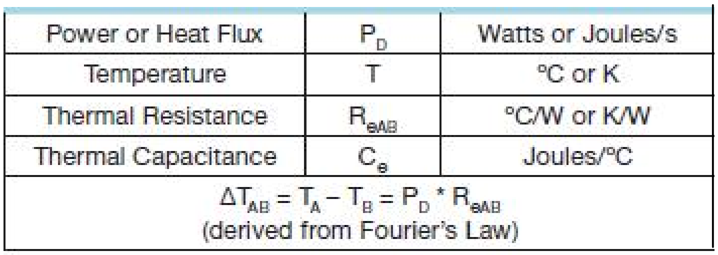
TA	Temperature at reference point “A”
TJ	Junction temperature, often assumed to be constant across the die surface
TC or TCase	Package temperature at the interface between the package and its heatsink; should be the hottest spot on the package surface and in the dominant thermal path

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_{QAB}	Thermal resistance between reference points “A” and “B, or R_{THAB}
R_{QJMA}	Junction to moving air ambient thermal resistance
R_{QJC}	Junction to case thermal resistance of a packaged component from the surface of its silicon to its thermal tab, or R_{THJC}
R_{QJA}	Junction to ambient thermal resistance, or R_{THJA}
C_{QAB}	Thermal capacitance between reference points “A” and “B”, or C_{THAB}
C or K Degrees	Celsius or degrees Kelvin
Z_{QAB}	Transient thermal impedance between reference points “A” and “B”, or Z_{THAB}

Basic Principles



Analogous to the electrical domain, power flows between points of temperature difference as shown above. Or conversely power flow through a thermal resistance creates a temperature difference.



Power or Heat Flux	P_D	Watts or Joules/s
Temperature	T	°C or K
Thermal Resistance	$R_{\theta AB}$	°C/W or K/W
Thermal Capacitance	C_θ	Joules/°C
$\Delta T_{AB} = T_A - T_B = P_D * R_{\theta AB}$ (derived from Fourier's Law)		

From the relationships above,

ΔT_{JA} $= (T_J - T_A) = P_D R_{QJA}$

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

T_J $= T_A + (P_D R_{QJA})$ (Eq. 1)

For example, let's assume that:

R_{QJA} = 30.deg C/W
P_D = 2.0W
T_A = 75.C

Then, by substitution:

T_J $= T_A + (P_D R_{QJA})$
T_J = 75.deg C + (2.0W * 30.deg C/W)
T_J = 75.C + 60.deg C
T_J = 135.deg 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.

Transient Thermal Response

Of course, the math extends to transient as well as steady state conditions. The existence of a thermal capacitance 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:

$\mathbf{T_Q} = R_Q C_Q$ (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:

$\mathbf{C_Q} = q\ t/\Delta T$ (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:

$\mathbf{C_Q} = c.d.V$ (Eq. 4)

where:
c = specific heat (J kg-1 K-1)
d = density (kg/m3)
V = volume (m3)

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

$\Delta T_{AB} = R_{QAB}\ P_D\ (1 - e^{(-t/T)})$

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.

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

$q = k\ A\ \Delta T$ (Eq. 5)

where:
q = heat transferred per unit time (J/s)

k (or h) = convective heat transfer coefficient of the process (W m^{-2} .deg C^{-1})

A = heat transfer area of the surface (m^2)

ΔT = temperature difference between the surface and the bulk fluid (deg 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:

$$q = \varepsilon \sigma A (T_h^4 - T_c^4) \qquad \text{(Eq. 6)}$$

where:
q = heat transfer per unit time (W)
ε = emissivity of the object (1.0 for a black body)
σ = Stefan-Boltzmann constant = 5.6703*10-8 (W m^{-2} K^{-4})
A = area of the object (m2)
T_h= hot body absolute temperature (K)
T_c= cold surroundings absolute temperature (K)

For geometries and temperatures typical of semiconductor packages, radiation is not a primary transport mechanism.

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 1. 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 325.C.

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 <u>gate-source threshold voltages fall with temperature</u>. 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 <u>permanent damage may ensue.</u>

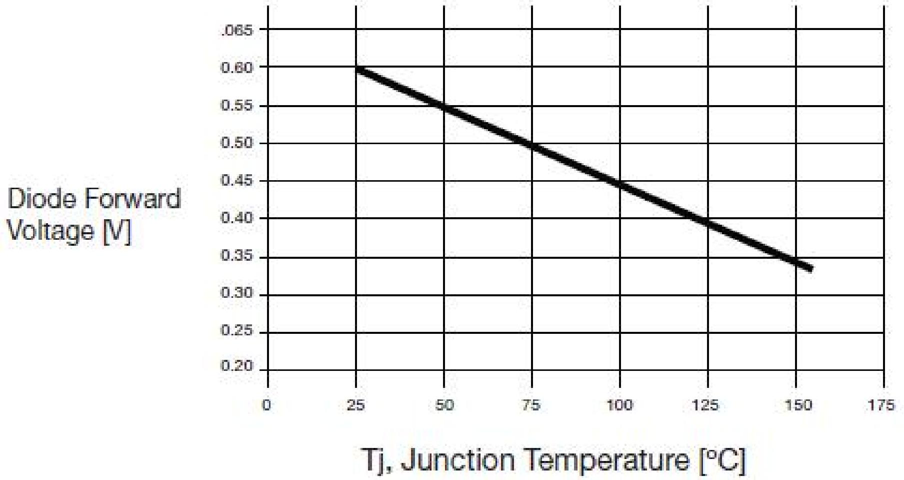


Figure 1.0

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 speed slows
- Bipolar transistor gains tend to fall
- Breakdown voltages tend to increase
- Transistor Safe Operating Areas decrease

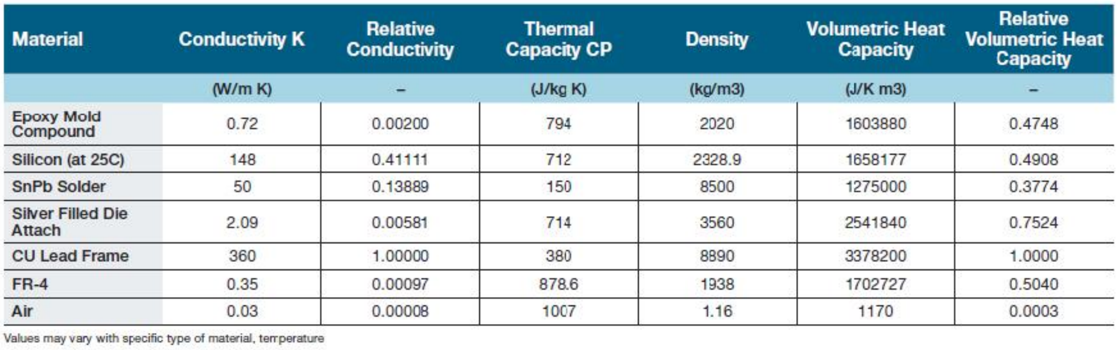
Knowing some of the critical temperature milestones and thresholds is helpful in selecting the appropriate temperature ratings of other components and for conducting forensic activity.

-55.deg C	Minimum semiconductor storage temperature
-40. deg C	Minimum automotive operating temperature
60. deg C	Metal surfaces are painfully hot
85. deg C	Maximum temperature of many electrolytic capacitors
125 deg C	Maximum operating temperature of many digital circuits
130 deg C	Common FR4 circuit board maximum temperature rating
150. deg C	Typical maximum junction temperature rating
165. deg C to 185. deg C	Typical power transistor over- temperature shutdown
155. deg C to 190. deg C	Mold compound's glass transition temperature*

183. deg C	Melting point of Sn63Pb37 solder (63% tin, 37% lead, eutectic)
188. deg C	Melting point of Sn60Pb40 solder
217 to 220 deg C	Melting point of Sn96.5Ag3.0Cu0.5 (96.5% tin, 3% silver, 0.5% copper)
280. deg C	Typical melting point of die attach solder
~350. deg C	Diode Vf approaches 0V
660 deg C	Melting point of pure aluminum (wirebonds and metallization are often aluminum)
1400. deg C	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.

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

Thermal modeling

The following sections cover the basics of thermal modeling in conceptual form.

Thermal RC modeling

This modeling method uses electrical RC network equivalents to represent the equivalent thermal behavior of the module, based on the use of discrete thermal components. These components are determined from the geometric and material characteristics of the module, and coded as a device to be used in a circuit analysis environment, so it is coupled with the electric circuit of the module to allow for the simulation of a complete electro-thermal model. These reduced order models are also computationally faster than the 3D finite element modeling approaches of many thermal design and analysis tools, and are a better alternative for the virtual prototyping approach being followed in fast analysis.

Practically all thermal RC models have certain things in common when it comes to generating a thermal model for an electronic subsystem. The principal one is, that the suggested model follows a current-power analogy. Heat dissipation behaves naturally as charge flow does in electrical circuits, heat capacity related to capacitances and heat dissipation to resistances.

It is necessary to recognize the relevant heat-transfer mechanisms and their governing relations in order to understand the flow of heat within electronic systems. Three mechanisms can be considered: conduction, convection, and radiation. Heat conduction occurs when heat diffuses through a solid or a stationary fluid.

In the MCM, conduction will occur from the junctions through the solid module materials. Heat convection occurs when a fluid in motion assists heat transfer from a wetted surface. The heat sink performs this transfer from the module structure to the surrounding air.

Heat radiation is the heat exchange between a surface and a surrounding fluid if long-wave electromagnetic radiation is the transfer agent. Its contribution is more noticeable when high temperatures are present, but in the case of the MCM, conduction and convection practically dominate the whole process due to the allowed operational temperature range, which states that the junction temperatures must be less than 125°C.

ONE-DIMENSIONAL MODELING APPROACH

Steady thermal transport through solids is governed by the Fourier equation which in one-dimensional form is expressible as

$$q = -kA\frac{dT}{dx} \qquad \text{Eq 7.0}$$

where

q	is the heat flow,
k	is the thermal conductivity of the medium,
A	is the crosssectional area for the heat flow, and
dT/dx	is the temperature gradient in the direction of the heat flow.

Heat flow produced by a negative temperature gradient is considered to be positive, and that is the reason for the minus sign in the previous equation.

The temperature difference resulting from a steady state diffusion of heat will be related to k, A, and the path length L by:

$$\Delta T = (T_1 - T_2)_{cd} = q\frac{L}{kA}$$

in degrees K. Eq 8.0

Ohm’s Law governing electrical current flow through a resistance can be used as an analogy to define thermal resistance for conduction as:

$$R_{cd} \equiv \frac{(T_1 - T_2)}{q} = \frac{L}{kA} \qquad [\mathrm{K/W}].$$

Eq 9.0

It can be seen from these equations that, in terms of electrical circuit variables, temperature would be equivalent to voltage, and heat flow would be equivalent to current in a circuit. These equalities were addressed above. It is important to notice that, if no physical resistor is present as an available path, there will be no current flow in presence of a voltage potential, but *that is not necessarily true in the thermal equivalent*. Even if there is no material present with a difference in temperature between its extremes, heat flow can still be existent due to radiation effects when a temperature differential is present. That is how heat can flow even in vacuum conditions.

Following the analogies, if a heat flow is equivalent to an electrical current, then instantaneous heat should be equivalent to electrical charge. Heat
capacity, which is usually identified as the specific heat C_p times volume, is given in units of Joules/Kelvin/cm3 and defined as the amount of heat necessary to raise the temperature of 1 unit mass of substance by 1°C. The total heat is then dependent on the amount of material available to store it (volume).

The thermal flow associated with this
quantity will be:

$$q = (C_p V)\frac{dT}{dt} \qquad [\mathrm{W}].$$

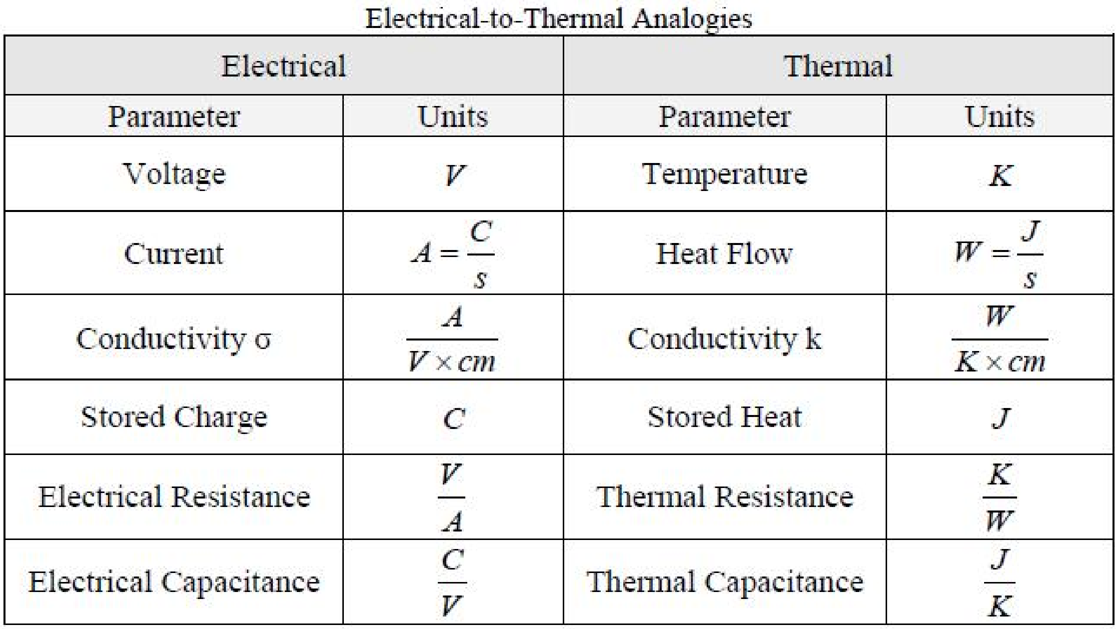
Eq 10.0

If the same electrical analogy must hold for the thermal case, then the thermal or heat capacitance associated with the heat conduction through the material volume will be given as:

$$C_{cd} \equiv C_p V \qquad [\mathrm{J/K}].$$

Eq 11.0

Table 1 below re-summarizes part of the voltage-temperature analogy that will be helpful in developing the thermal component model.



Electrical-to-Thermal Analogies

Electrical		Thermal	
Parameter	Units	Parameter	Units
Voltage	V	Temperature	K
Current	$A = \frac{C}{s}$	Heat Flow	$W = \frac{J}{s}$
Conductivity σ	$\frac{A}{V \times cm}$	Conductivity k	$\frac{W}{K \times cm}$
Stored Charge	C	Stored Heat	J
Electrical Resistance	$\frac{V}{A}$	Thermal Resistance	$\frac{K}{W}$
Electrical Capacitance	$\frac{C}{V}$	Thermal Capacitance	$\frac{J}{K}$

Table 1.0

For example, if heat is being applied to one extreme of a body made out of two different materials, with ambient temperature surrounding the rest of it. A one dimensional thermal equivalent could be like the one shown in Figure 2(a).

The thermal power source will deliver a certain amount of heat that will be distributed through the entire body until a thermal equilibrium is reached. Figure 2(a) is not the only way to represent the thermal network using an RC equivalent. Some other variations are also presented. Figures 2(b), (c) and (d) are referred to as a Foster network, a Cauer network, and a Cauer network for a top-covered device, respectively.

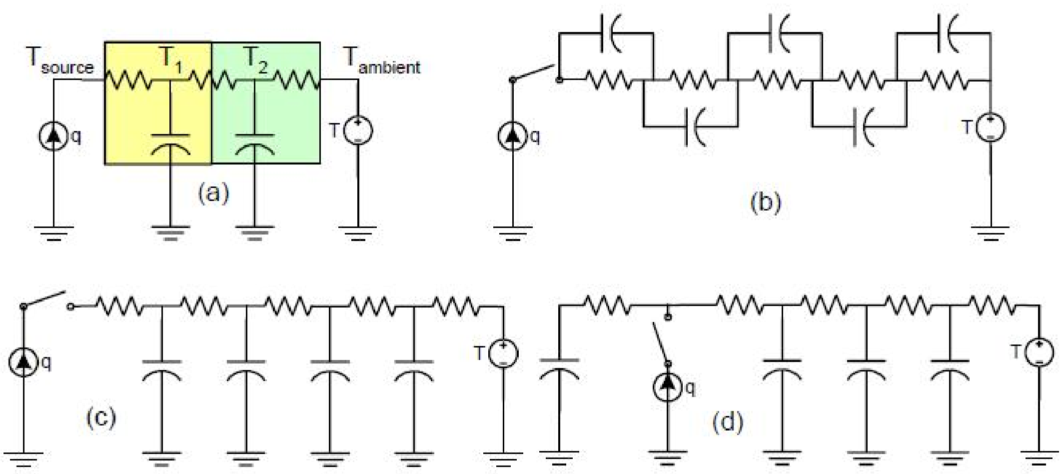


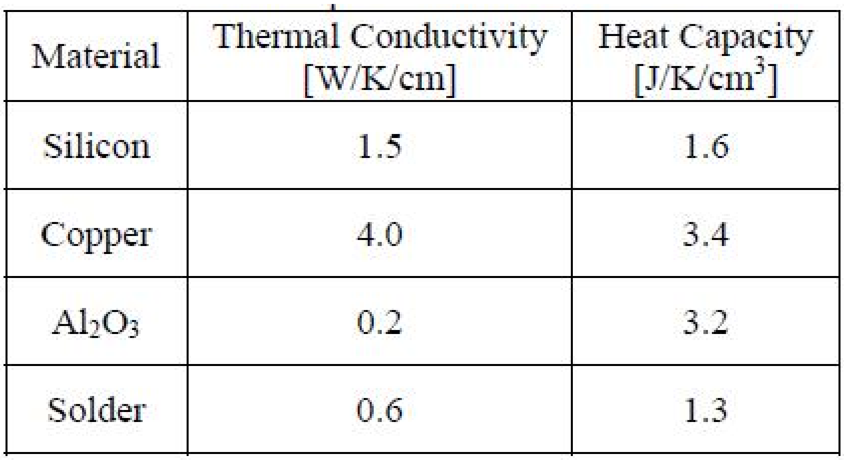
Figure 2.0 Example of one-dimensional thermal networks: (a) general approach; (b) Foster network; (c) Cauer network for a top uncovered device; (d) Cauer network for a top covered device.

Only the Cauer circuits are suitable for faithfully representing the system from the physical point of view. That happens because a dramatic physical nonsense occurs if the Foster network is applied for interpreting the dynamic thermal behavior of the internal points in the circuit. In the electrical circuit, the current flowing across the capacitor during a dynamic regime is the same on both sides of the device due to the symmetrical variation of the positive and negative electric charges. But thermal circuits have no quantities equivalent to negative electric charge. Only the heat flow on one side of the capacitor has a real meaning, and that is why the Cauer networks, with their capacitors grounded on one side, are more suitable as a thermal analogy.

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 MCM is a structure with different layers and materials of varying dimensions. In order to find the correct thermal resistances and thermal capacitances that would represent the MCM thermal model, it is important to know all the physical dimensions of the MCM and the thermal characteristics of all the materials involved in its construction.

Thermal properties of some materials are shown below:



Material	Thermal Conductivity [W/K/cm]	Heat Capacity [J/K/cm^3]
Silicon	1.5	1.6
Copper	4.0	3.4
Al_2O_3	0.2	3.2
Solder	0.6	1.3

A good engineer will want to consider several aspects of this representation. First what 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 (a variable that is applied *across* a component) 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 the figure above connects the capacitor to the reference terminal. 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 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 the figure is of a single heat source and consequently lacks any provision for thermal coupling between neighboring components. For circuits with multiple power dissipating elements the components in the figure 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.

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. We 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. The following 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 lead frame. 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.

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.

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.

Rebeca 3D, a BEM package supplied by Epsilon Ingenierie, can be used 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.

See appendix 1.0 for some common materials used in semiconductor packaging and MCMs.

Empirical Analysis

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 of 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.

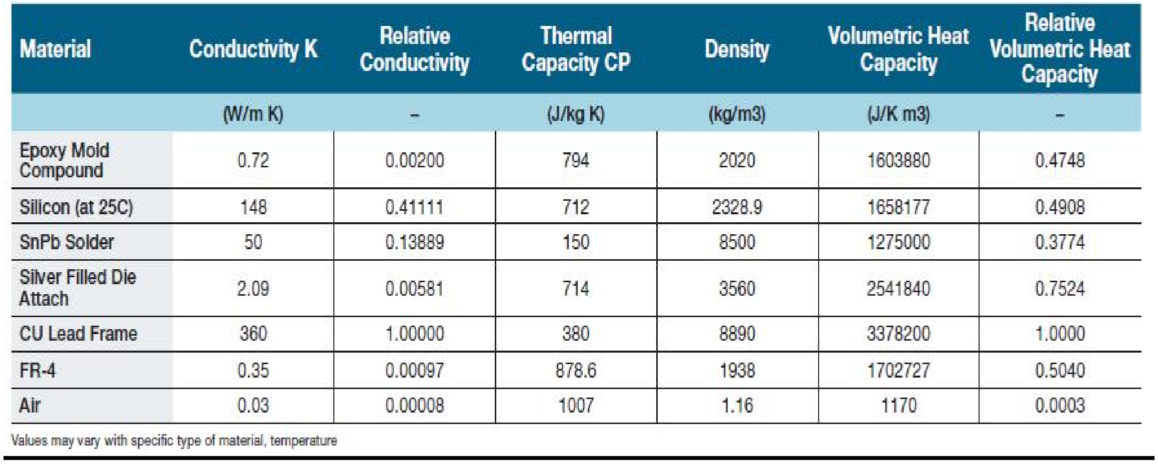
If you are designing a system that has a predecessor, use data from that module as a starting point. If the system has no predecessor, then consider building a thermal mock-up that will mimic the final module's behavior. Such a mock-up might have little or no electrical similarity to the intended module, 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.

Appendices

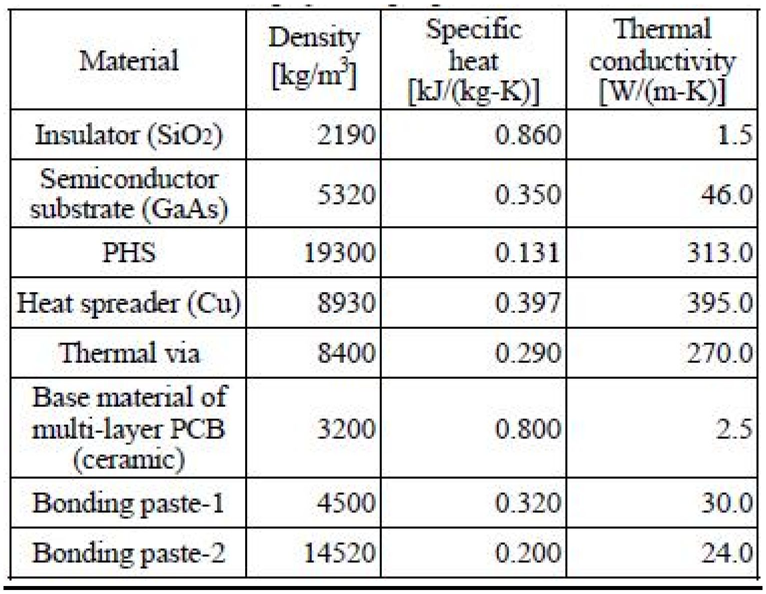
A1.0 Thermal properties of common semiconductor packaging materials.



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

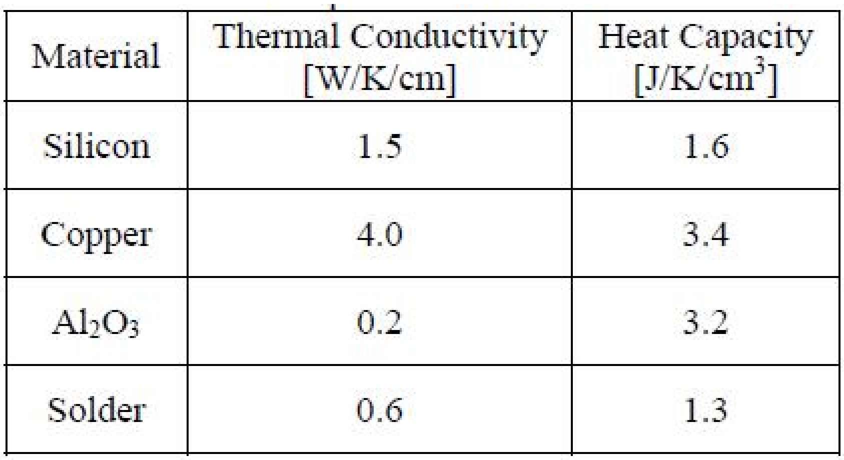
A2.0 Thermophysical properties of pertinent materials



Material	Density [kg/m^3]	Specific heat [kJ/(kg-K)]	Thermal conductivity [W/(m-K)]
Insulator (SiO_2)	2190	0.860	1.5
Semiconductor substrate (GaAs)	5320	0.350	46.0
PHS	19300	0.131	313.0
Heat spreader (Cu)	8930	0.397	395.0
Thermal via	8400	0.290	270.0
Base material of multi-layer PCB (ceramic)	3200	0.800	2.5
Bonding paste-1	4500	0.320	30.0
Bonding paste-2	14520	0.200	24.0

- PHS = plated heat sink.

A3.0 Thermal properties of some semiconductor materials



Material	Thermal Conductivity [W/K/cm]	Heat Capacity [J/K/cm^3]
Silicon	1.5	1.6
Copper	4.0	3.4
Al_2O_3	0.2	3.2
Solder	0.6	1.3