PRINCIPLES OF POWER ELECTRONICS

Second Edition

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25 Thermal Modeling and Heat Sinking

An unfortunate consequence of our preoccupation with things electrical is that the problems of heat sinking and thermal management are frequently ignored until forced on us by sound, sight, or smell. The insatiable need to make things smaller — and the possibility of doing so by using higher frequencies and new components and materials — aggravates the problem of heat transfer, because such improvements in power densities are seldom accompanied by corresponding improvements in efficiency. Thus we are stuck with the task of getting the same heat out of a smaller volume while disallowing any increase in temperature.

The diversity of heat sources within power electronic apparatus produces a challenging cooling problem. Unlike signal processing circuits — where most heat-generating components come in a common, small, and low-profile rectangular package — energy processing circuits contain components of odd shapes and orientations. Even those of the same type come in many different forms and packages. Inductors, for instance, can be small or large, round or rectangular, and with loss dominated by core or copper. Each possesses special requirements and presents a unique thermal problem. The task of integrating these parts into a reliable piece of equipment becomes as much a thermo-mechanical challenge as the circuit design was an electrical challenge.

Heat transfer occurs through three mechanisms: conduction, convection, and radiation. In conduction the heat transfer medium is stationary, and heat is transferred by the vibratory motion of atoms or molecules. Convective heat transfer occurs through mass movement — the flow of a fluid (gas or liquid) past the heat generating apparatus. In *natural-convection*, the buoyancy created by temperature gradients causes the fluid to move; in a *forced-convection* system, the mass flow is created by pumps or fans.

Heat transfer by radiation turns the heat energy into electromagnetic radiation, which is absorbed by other elements in the environment. Radiation as a mechanism of heat transfer is important for space applications but less so for terrestrial power electronic systems. Heat transferred through radiation is a function of the temperatures, T_S and T_R respectively, of the radiating element's surface and the receiving surface (which may be a surface in the surrounding environment at a remove from the hot component). Specifically,

$$Q_{\mathrm{rad}} \propto T_S^4 - T_R^4$$

Radiation may be important in equipment where this difference is large. However, the strong nonlinearity of this relationship and the relatively low incidence of its importance do not justify the complexity of considering radiation in detail here. Therefore in this chapter we focus on conduction and convection.

If only these two mechanisms are considered, the design will be conservative, as any heat transferred through radiation will reduce the temperature of the apparatus below the design temperature. The exception is in enclosures, where radiation from hot components may be absorbed by those at lower temperatures, causing these latter components to operate at higher temperatures than anticipated. In such cases, radiation shields — shiny metal partitions — can be employed to isolate the offending or affected components.

The material in this chapter will not give you novel ideas for designing heat transfer systems. The problem is too application-specific to permit such a discussion to be of value. Instead, we describe first the parameters governing the performance of any such system. Then we consider the modeling of both steady-state and transient thermal behavior, as applicable to power electronic systems. Some straightforward examples of specific designs will be presented to illustrate the discussions.

25.1 Static Thermal Models

Circuit theory is the *lingua franca* of engineering for good reason. The elegance and simplicity of its canonical formulations (for example, KCL and KVL) permit complex problems to be approached in an organized way, and the insights gained through such formulations are extremely valuable in predicting system behavior. Therefore many engineering problems in contexts other than electrical engineering — particularly in the setting of 'flows' driven by 'gradients' — are cast in terms of circuit models before being analyzed. One of these contexts is heat transfer.

25.1.1 Analog Relations for the DC Case

The rate at which heat energy is transferred by conduction from a body at temperature T_1 to another at temperature T_2 is denoted by Q_{12}. It is well modeled as linearly proportional to the temperature difference between the two bodies, $T_1 - T_2$, and inversely proportional to a physical parameter called the *thermal resistance* between them, R_θ:

$$Q_{12} = \frac{T_1 - T_2}{R_\theta} = \frac{\Delta T}{R_\theta} \tag{25.1}$$

The analogy with Ohm's law is evident, and we can make the following assignment of variables:

$$T_{1,2} \Longleftrightarrow v_{1,2} \qquad Q_{12} \Longleftrightarrow i \quad \text{and} \quad R_\theta \Longleftrightarrow R \tag{25.2}$$

Note that the analog of thermal power is i, not vi. If heat leaves body 1 only through the interface characterized by R_θ, then i is not only analogous to Q_{12}, but, because we are considering only steady-state conditions, it also represents the rate at which energy is being converted to heat in body 1. In the context of our interests, body 1 would be a packaged electrical network, and Q_{12} would represent the rate at which electrical energy is being converted to heat (dissipated) in the package, that is,

$$p_{\text{diss}} \Longleftrightarrow i$$

The thermal management problem is to design a heat transfer system (that is, R_θ) that constrains ΔT to the value dictated by component ratings and ambient conditions.

Figure 25.1 illustrates the electrical analog for the simple two-body system just discussed. The bodies are at temperatures T_1 and T_2 and are connected thermally through the crosshatched interface, which can be characterized by a thermal resistance of value R_θ. If the units of T are °C and the units of Q are watts (W), then thermal resistance has the units °C/W. As with electric circuits, where parallel resistances can be combined into a single equivalent resistance, parallel thermal paths can be characterized by thermal resistances and combined into an equivalent single thermal resistance.

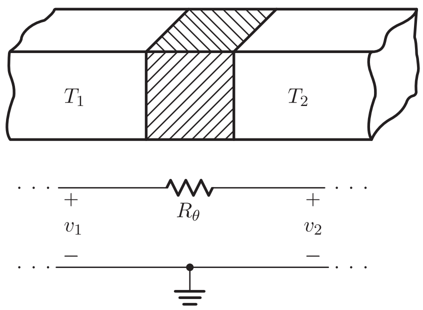


Figure 25.1 Electrical analog of simple two-body thermal system. The crosshatched region is the thermal interface characterized by the longitudinal thermal resistance R_θ.

Convection is the mechanical transport of heat by a moving fluid. The fluid (air, for instance) can move because of gravitational forces caused by density gradients, in which case the process is called natural convection. Or the fluid can be driven (perhaps by a fan), resulting in what is called forced convection. Convection is a somewhat more complex process than conduction and can be described by the relation

$$Q_{12} = h(\Delta T, \nu)A(T_1 - T_2) \tag{25.3}$$

where ν is the fluid velocity. The parameter $h(\Delta T, \nu)$ is termed the *film coefficient of heat transfer*; it depends on fluid velocity and the difference between the inlet and outlet temperatures. The cross-sectional area of the interface is A. Over the range of temperature differentials of interest in our application, h is fairly constant. With respect to fluid velocity, significant changes in h occur when the flow regime changes from laminar to turbulent. Within each regime, however, h improves only slowly with increased velocity. For forced convection, h is independent of ΔT. Within these limits, the product hA may be modeled as constant, giving to (25.3) the same form as (25.1), with $R_\theta = 1/hA$. Thus the electrical analog shown in Fig. 25.1 is appropriate for representing convective as well as conductive heat transfer.

25.1.2 Thermal Resistance

As we have just shown, a thermal resistance can be used to model both conductive and convective heat transfer. The physics governing thermal conduction is much like that for electrical conduction, and the thermal resistance or conductance can be described in terms of parameters abstracted from the physics of the process (for example, conductivity) and geometry. In fact, thermal and electrical conductivity of a material are intimately related by the *Wiedemann–Franz law*, which states that the ratio of these conductivities varies linearly with temperature T (so is fixed at a given T). — materials of high electrical conductivity are also good thermal conductors.

Convection, however, depends on parameters that are not so easily abstracted. For instance, while conductivity can be adequately described in terms of material type and temperature, h is a function not only of these parameters but also of velocity, surface characteristics, and geometry. The latter parameter often also determines the *Reynolds number*, a dimensionless number that indicates whether laminar or turbulent flow will occur in a particular situation. Furthermore, the geometry of the convective part of the system is invariably complex, consisting quite often of a finned aluminum extrusion. Thus the equivalent thermal resistance model for convective transfer from a specific heat sink type in a variety of environments (for example, forced or natural convection) is tabulated by the manufacturer. For this reason, the following discussion is directed at determining the equivalent thermal resistance for those parts of the system where heat transfer is by conduction.

The analog of electrical resistivity (Ω-m, or more commonly, Ω-cm) is thermal resistivity, ρ_θ, in units of °C-cm/W (or K-cm/W as Kelvin is often used instead of Celsius). In terms of ρ_θ and physical dimensions, the longitudinal thermal resistance of a piece of material of cross-sectional area A and length l is

$$R_\theta = \frac{\rho_\theta l}{A} \quad {}^\circ\mathrm{C/W} \tag{25.4}$$

An alternate definition of thermal resistance, used for sheet material, incorporates the sheet thickness. The conductance through a sheet of unit area and specified thickness is given by the parameter h_c having units of W/K-cm^2. Therefore the resistance of an area A of the sheet is

$$R_\theta = \frac{1}{h_c A} \quad {}^\circ\mathrm{C/W} \tag{25.5}$$

The thermal resistivities of various materials used in heat transfer paths in electronic equipment are shown in Table 25.1. Mylar, and less commonly mica, is used to provide electrical isolation between electrically hot components (for example, the semiconductor device package and the heat sink). Mica has a much higher dielectric strength, is more impervious to mechanical puncture, and can be cleaved to produce thinner sheets than Mylar—but is more expensive. Beryllia (BeO) and alumina (Al_2O_3), and recently aluminum nitride (AlN), are also used to provide electrical isolation, most frequently within device packages. Silicone grease impregnated with metallic oxides, such as

Table 25.1 Thermal Resistivities of Materials Used in Electronic Equipment

MATERIAL	THERMAL RESISTIVITY (°C-m/W)
Still air	30.50
Mylar	6.35
Silicone grease	5.20
Mica	1.50
Filled silicone grease	1.30
Filled silicone rubber	1.0
Alumina (Al_2O_3)	0.06
Silicon	0.012
Beryllia (BeO)	0.01
Aluminum Nitride (AlN)	0.0064
Aluminum	0.0042
Copper	0.0025

ZnO_2, is used to fill imperfections such as scratches on mating surfaces in a heat transfer path — between the bottom of a device package and the top of a heat sink, for instance. The need to fill these voids with something other than air is apparent from the table. Filled silicone grease is also referred to as *thermal grease* or *thermal compound* (or "goop", for reasons that become clear when you use it). Anodizing is frequently used to create an attractive or black surface on aluminum components. Since the resulting oxide is very thin, it contributes little to the thermal resistance of a path. Although the oxide is a good insulator, it is unwise to rely on it in lieu of a dielectric material for providing electrical isolation between surfaces.

Example 25.1 A Calculation Using An Electrical Analog

Figure 25.2(a) shows a resistor embedded in the center of a 10 cm long block of aluminum whose ends are at temperature T_A. What is the temperature of the resistor if it is dissipating 50 W and the ambient temperature is $T_A = 75°C$?

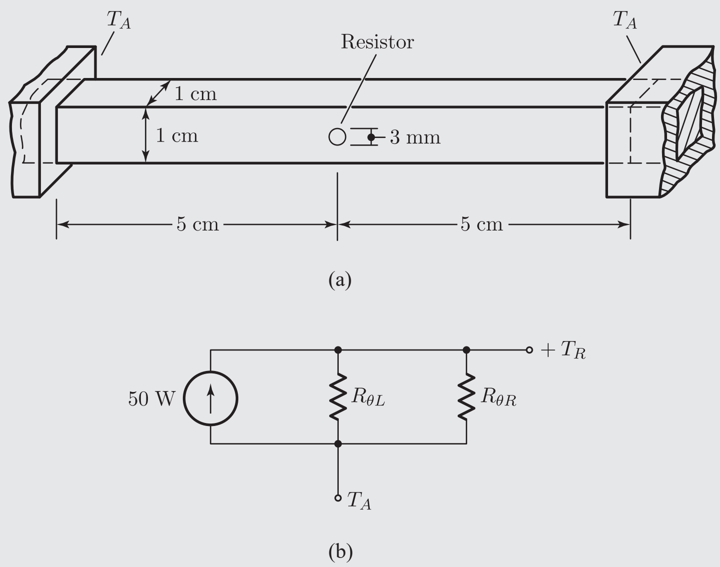


Figure 25.2 (a) A thermal system consisting of a resistor embedded in the center of an aluminum block. (b) The electric circuit analog for the thermal system of (a).

As the length of the block (10 cm) is much longer than the radius of the resistor (3 mm), we can assume that the detailed pattern of heat flow in the vicinity of the resistor is unimportant. The resulting analog circuit model is shown in Fig. 25.2(b), where $R_{\theta L}$ and $R_{\theta R}$ are the thermal resistances of the aluminum bar to the left and right of center. The value of these resistances are

$$R_{\theta L} = R_{\theta R} = \frac{(0.42)(5)}{1} = 2.1^{\circ}\text{C/W} \tag{25.6}$$

At a dissipated power of 50 W, the temperature of the resistor, T_R, is

$$T_R = 75 + 50\left(\frac{2.1}{2}\right) = 127.5^{\circ}\text{C}$$

25.2 Thermal Interfaces

A critical part of any heat transfer system is the interface between mechanical components in the thermal path. Some issues related to these interfaces in the context of our application were raised in the previous section. The geometry of most interfaces can be modeled as two parallel planes with material of a specific thermal resistivity between. If the material is of thickness δ and of area A, the thermal resistance of the interface between the planes is

$$R_{\theta i} = \frac{\rho_\theta \delta}{A} \tag{25.7}$$

Consider for example a device in a TO-220 package mounted on a heatsink. Between the device and heatsink is a 1.6 mm alumina pad because electrical isolation between the device and heatsink is required. The mating surface area of a TO-220 package is approximately 0.95 cm^2, giving a thermal resistance between the case and the sink of:

$$R_{\theta CS} = \frac{(6)(0.16)}{0.95} = 1.01°\mathrm{C/W} \tag{25.8}$$

Thus the difference between the case and sink temperatures increases by 1.01°C for each watt of thermal power being transported across the interface. A dissipation of 15 W is not unusual for a device in a TO-220 package, giving a temperature rise of 15.2°C across just the alumina interface. This amount, which does not include the thermal resistance of the interfaces between the alumina pad and the TO-220 case or heatsink, is significant, and illustrates the price paid for requiring electrical isolation.

Example 25.2 A Thermal System

The physical structure depicted in Fig. 25.3 is typical of the thermal system that results from mounting a semiconductor die. The device itself is bonded to the header using solder or epoxy; the header is made part of a package that is mounted to a heat sink (perhaps with some intervening insulating material); and the heat sink is thermally connected to the ambient environment, generally through free or forced (fan) convection. A highly detailed model for this system is shown in Fig. 25.4(a), where each part of the system is explicitly represented by its equivalent thermal resistance. The model also shows the relationship between certain node voltages and the temperatures they represent. The current source represents the rate at which electrical energy is dissipated in the device, P_{diss}. The physical location within the device of this dissipation is the node to which the source is connected, the junction in this case.

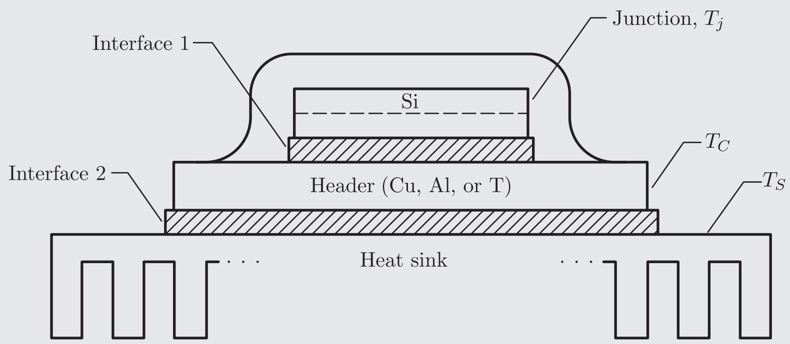


Figure 25.3 Typical mechanical structure used for mounting semiconductor die.

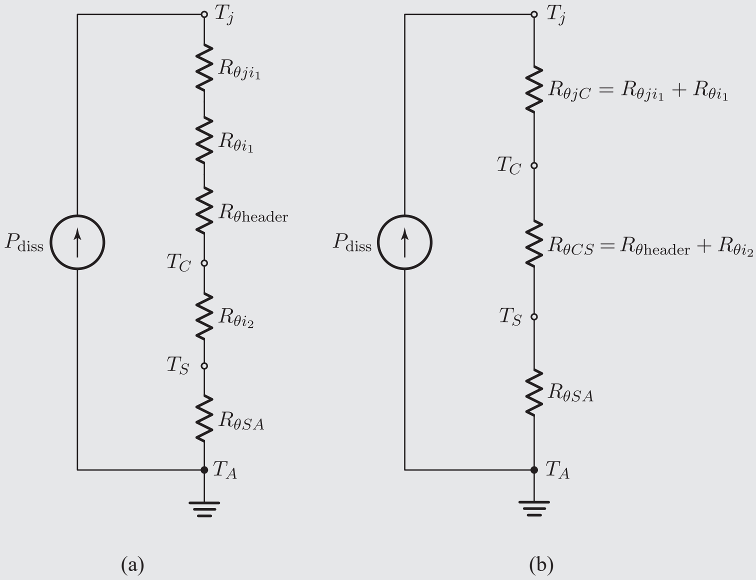


Figure 25.4 (a) A static thermal model for Fig. 25.3. (b) A simplified model of the circuit in (a).

Some of the thermal resistances shown in Fig. 25.4(a) are so small relative to others that they can be neglected. Because the header is made of copper or aluminum, its vertical thermal resistance is negligible, as is that of the thermal grease (assuming that it is applied properly, which it often is not!). Others of the identified resistances are frequently lumped together, such as those for the silicon and bonding material, which are generally inaccessible to the circuit designer. Implicit in the element $R_{\theta SA}$ are the thermal resistance of the sink extrusion between the region on which the package is mounted and the surfaces from which heat is being removed by convection, and the thermal resistance representing the convection process. Figure 25.4(b) shows the simplified model.

The variable of interest in the models of Fig. 25.4 is T_j, the "junction" temperature of the device. The term "junction" is used rather loosely to represent in lumped form the source of heat in the device. In reality, this source seldom exists as a simple plane. In the MOSFET it is not a junction at all. Nevertheless the term persists, and manufacturers determine $R_{\theta jC}$ empirically, which takes into account the actual geometry of the heat-producing region. To determine T_j, we need to know P_{diss} as well as the thermal resistances between the junction and the ambient environment.

The dissipation in the device is a function of its electrical environment (for example, its current, voltage, and switching loci). For the purposes of this example, we assume that these calculations have been made for our device, and that the result is $P_{\text{diss}} = 25$ W. The physical configuration is a TO-247 package mounted on an extruded, finned, free convection-cooled sink without any insulating interface but with thermal grease. Typical values of the thermal resistances are $R_{\theta jC} = 1.1$, R$_{\theta CS}$ = 0.12, and $R_{\theta SA} = 1.8$, all units being °C/ W. The last parameter needed is the ambient temperature, which is not "room temperature," but that of the air in the vicinity of the sink. We take it to be 40°C. We determine the temperature drop between nodes in the model by using Ohm's law, obtaining

$$T_S = 40 + (25)(1.8) = 85°\text{C}$$
$$T_C = 85 + (25)(0.12) = 88°\text{C}$$
$$T_j = 88 + (25)(1.1) = 115.5°\text{C}$$

Is this an adequate design? The answer depends on the type of device being cooled. If it were a Si MOSFET, the design gives a good margin between predicted junction temperature and typical maximum limits of 150°C. For a thyristor the design is marginal.

25.2.1 Practical Interfaces

Mechanical interfaces are not parallel in practice. They contain surface imperfections, such as scratches, and a characteristic called *run-out*. Run-out is the maximum deviation from flatness that a surface exhibits over a specified lateral distance. It is measured in (linear dimension)/(linear dimension), for example, cm/cm. A standard aluminum extrusion exhibits run-out that is typically 0.001 cm/cm. Both scratches and run-out degrade the thermal performance of an interface. Run-out is generally not under the design engineer's control. Therefore we must measure or estimate it and make proper allowance for it. However, run-out is seldom an issue with modern commercial heat sinks.

The use of thermal grease has already been mentioned. It is designed to reduce the degrading effects of surface scratches and other small imperfections but is not designed to remedy the effects of run-out. Although our primary focus is on basic principles, thermal grease is so frequently misused that a brief departure from "principle" to "practice" is justified. The problem arises from a belief that if a little is good, a lot is better. However, the art of applying thermal grease is much like that of watering plants—too much and it's dead. Silicone grease is highly viscous and refuses to "squish out" when squeezed between header and sink by mounting hardware. In such cases, a thin layer of grease can remain in the interface, giving rise to a significant thermal resistance that was not anticipated in the thermal design. The grease should be applied sparingly, and then wiped off, removing almost all traces. Thermal grease oozing from under device packages is a sign of poor construction and potential thermal problems.

When electrical isolation between device and heat sink is required, a pad made of silicone (or other conformable material) can be used as an interface material. These "squishy" materials fill scratches and other surface imperfections when mounting pressure is applied and are available as sheets, or in shapes conforming to most device package geometries. A unique consideration when using these pads is that the resulting thermal resistance between the two surfaces is a function of mounting pressure. The relationship among $1/h_c$, thickness, and pressure is usually provided by the manufacturer[†].

The printed circuit board (PCB) presents unique thermal design problems. One can mount on the board heat sinks to which are attached the semiconductor devices, however this occupies valuable board real-estate. If the thermal requirements are not too severe, a common approach is to mount the device directly on the board over vias[†] that thermally connect the upper and lower layers of copper foil. The device is thermally connected to the upper foil layer, which spreads and dissipates the heat as well as transferring heat through the vias, where it is spread on the lower foil layer. This heat-sinking method for PC boards is illustrated in Fig. 25.5.

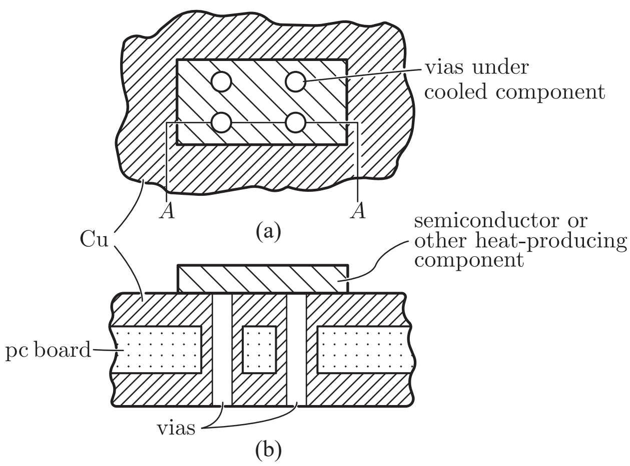


Figure 25.5 An illustration of the use of vias as heatsinks for components mounted directly to a PC board: (a) top view of device showing location of 4 vias; (b) cross-section A–A illustrating the copper plating in the vias.

25.2.2 The Convective Interface

Even though we showed that both conduction and convection processes could be modeled by similar electrical analogs, our discussion so far has focused on conduction interfaces. However, all conduction actually leads to a convective interface. Heat is

[†]Manufacturers of sheet material often use the term *thermal impedance* instead of resistance to denote $1/h_c$.

[†]A via is a hole through the board, the interior wall of which has been plated with copper. It may or may not connect different layers of copper foil. Vias may optionally be filled with copper or another material to reduce thermal resistance.

removed from a conventional finned sink by air flowing over the fins. A more sophisticated system incorporating a heat exchanger probably uses a liquid to move the heat from one place to another. These are convective processes. As mentioned earlier, the physics governing these processes is beyond our scope here, However, a short discussion of the application of finned sinks is helpful.

The critical issue in the application of finned sinks is to ensure that air flow through the fins is turbulent rather than laminar. Laminar flow, as the name implies, is the flow of a fluid in such a way that strata can be defined; that is, all flow is in one direction, with no mixing of strata. Turbulent flow, on the other hand, causes considerable mixing. Without such mixing, the particular stratum of fluid in contact with the fin would remain in contact with it for its entire length, resulting in a very low value for the film coefficient of heat transfer h, discussed in Section 25.1.1 Stated another way, the boundary layer next to the fin surface remains intact in laminar flow, preventing efficient heat transfer from the fin to the moving stream of air (or other fluid).

The transition between laminar and turbulent fluid flow is a function of many variables, however fin geometry and flow rate are the critical ones for our application. The relationship among fin spacing, flow rate, and the onset of turbulence is given by the Reynolds Number. A high Reynolds Number is characteristic of turbulent flow; a low number is characteristic of laminar flow. The Reynolds Number Re for a fluid flowing at velocity ν through a channel of width w is

$$Re = \frac{\rho \nu w}{\eta}$$

where ρ is the fluid density, and η is its coefficient of viscosity. This expression shows that fluid flowing in a wider channel will enter the turbulent flow regime at a lower velocity than that through a narrower channel. The point here is that, like thermal compound, more is not necessarily better. Because of reduced turbulence and flow rate, many closely spaced fins and a large surface area could result in poorer thermal performance than fewer, but more widely spaced fins and a smaller surface area.

Although we have been using the context of semiconductor heat sinks for this discussion, it is equally appropriate to the cooling geometry associated with other components. Closely spaced parts impede proper convective flow for the same reasons that too closely spaced fins do.

25.3 Transient Thermal Models

So far our discussion and models have been limited to systems in which both the energy being dissipated and the temperatures within the system are constant. Our models do not represent the thermal processes associated with start-up, where dissipation may be constant, but temperatures are climbing — or pulsed operation, where temperatures may be constant, but dissipation is not. The latter situation is the more important, for under such conditions the permissible instantaneous dissipation can be much higher than predicted by static thermal models. Essentially, the heat capacity of components or their constituent parts creates a low-pass filter, which in the limit of small bandwidth only responds to the dc in $p_{\text{diss}}(t)$.

Heat capacity is a measure of the energy required to raise the temperature of a mass by a specific amount. In SI units, it is specifically the energy in joules required to raise one kilogram of the material one centigrade degree, and has the units /°C-kg. Water has one of the largest thermal capacities of any fluid at room temperature: 4.2×10^3 J/°C-kg. Masses in a thermal system, then, constitute thermal energy storage devices, and thermal systems containing mass will exhibit dynamic behavior.

25.3.1 Lumped Models and Transient Thermal Impedance

Since thermal power is Q, the analog of thermal capacitance is electrical capacitance in the circuit model for heat transfer. In its simplest form, then, the dynamic model for a mass being supplied with heat energy is an RC circuit, as in Fig. 25.6. If the heat source is constant, the final temperature is analogous to the final capacitor voltage, that is, $R_\theta Q$. Previously we have dealt with the steady-state solutions to such thermal systems. Now we are concerned with the transients leading to these steady states.

The temperature curve of Fig. 25.6(d) predicts the temperature T_1 as a function of time for a step P_o in thermal power. If this curve is normalized by the step amplitude (P_o in this case), the resulting vertical scale has the units of thermal impedance, that is, °C/ W. An experimentally or theoretically determined normalized curve of this kind is useful for predicting temperatures during thermal transients. The normalized quantity is a function of time and is called the *transient thermal impedance*, denoted by $Z_\theta(t)$:

$$Z_\theta(t) = \frac{T(t)}{P_0} \tag{25.9}$$

It is important to note that in order to properly represent the physics of the situation, thermal capacitances in a system model should always be connected to “ground”, that is, a reference temperature.

Distributed Models Energy in a mass is stored in a continuum. However, as is done for a transmission line, this continuum system may be modeled by an interconnection of lumped electrical elements. Consider, for instance, the mass of Fig. 25.6 with a source of heat energy applied at one end. The mass can be broken into an arbitrary number of sections, each assumed to be at a uniform temperature. Each such section is characterized by a heat capacity, and the sections are interconnected through a thermal resistance. This thermal resistance is that of the mass section between the interfaces with adjoining sections. This multi-lump model of the mass of Fig. 25.6 is shown in Fig. 25.7. The number of ‘lumps’, 5, was chosen arbitrarily.

When a continuous system is modeled by lumps, each lump displays the aggregate behavior of the physical piece of the system it represents. The model of Fig. 25.7 has

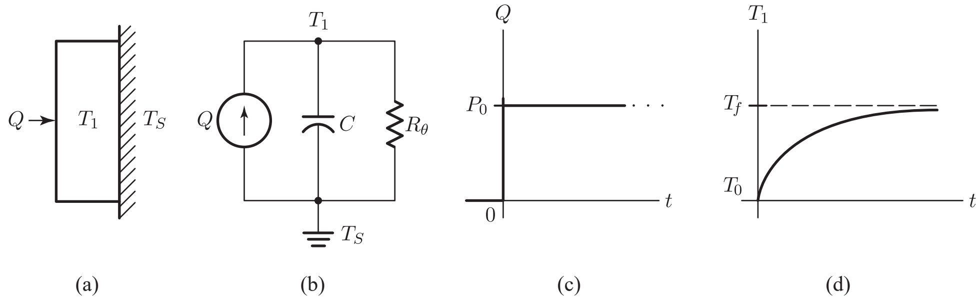


Figure 25.6 (a) A simple thermal system consisting of a mass at temperature T_1 being supplied heat Q and in contact with a sink at temperature T_S. (b) A single -ump dynamic model for the system shown in (a). (c) A step in thermal power exciting the thermal system of (a). (d) The temperature response of node T_1 to the excitation of (c).

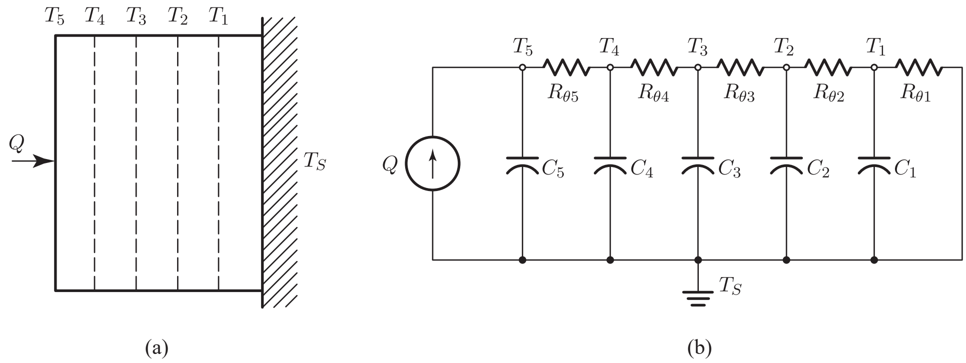


Figure 25.7 (a) The thermal system of Fig. 25.6(a) divided into five "lumps." (b) The lumped electrical analog model for the thermal system of (a).

been constructed so that the node voltages represent the section temperature aggregated at the interface. The number of lumps that should be chosen to represent a system depends not only on the spatial resolution of interest but on the bandwidth of the behavior being modeled. For instance, if Q is constant, no dynamics are excited, the bandwidth of the behavior is small, and a one-lump static model is adequate. However, if Q varies with time at a rate much greater than $(R_\theta C)^{-1}$ for the segments of Fig. 25.7, more lumps would be needed to accurately model the behavior of the system.

The device and package structure of Fig. 25.3 contains several thermal masses that contribute dynamics to its thermal behavior. These dynamics are important when the device is forced to dissipate high levels of power for short periods of time. "Short" is relative to the $R_\theta C$ time constant of the structure's electrical model. For very short pulses, the mass of the silicon is most important in determining the excursion of the junction temperature T_j. As the pulse gets longer, the mass of the header and then the heat sink become important. Manufacturers usually provide transient thermal impedance curves as functions of duty ratio and pulse width in the specification sheets for their devices. An illustrative set of curves for an SiC MOSFET in a TO-247 package is shown in Fig. 25.8. Only the bottom curve in this family is $Z_\theta(t)$ as defined by (25.9). The other curves are parametric in duty ratio for a series of pulses having a pulse width given on the x-axis.

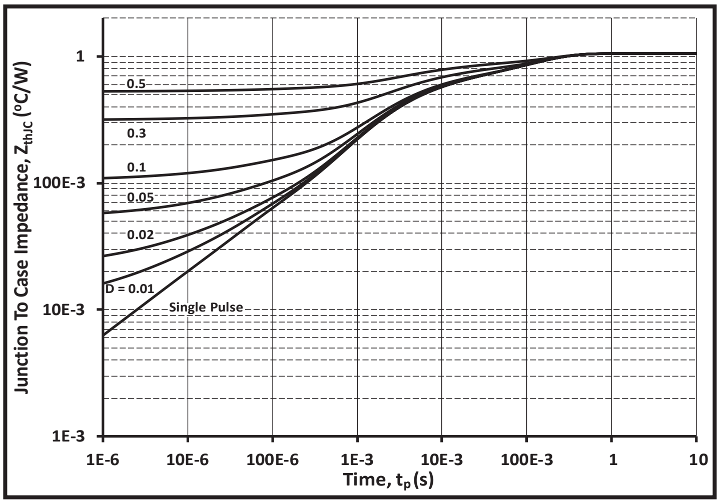


Figure 25.8 Transient thermal impedance, $Z_\theta(t)$, parametric in duty ratio and functions of pulse width t_p, for a 1200 V, 32 A Wolfspeed C3M0075120D SiC MOSFET in a TO-247 package. (Used with permission of Wolfspeed, Inc.)

Example 25.3 Transient Thermal Design for a MOSFET

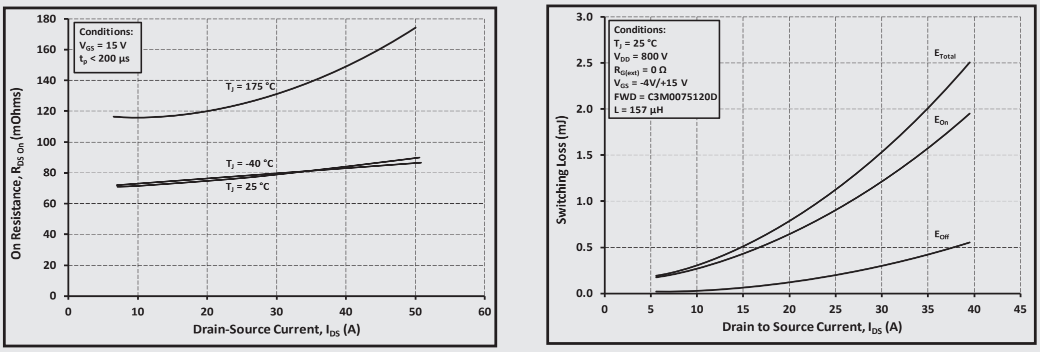
The Wolfspeed C3M0075120D SiC MOSFET rated at $V_D = 1200$ V and $T_j = 175°$C, whose transient thermal impedance characteristics are shown in Fig. 25.8, is used in an 800 V clamped inductive switching application. We consider an example in which it is subjected to repetitive 35 A current pulses with a duty ratio of 0.1 at a frequency of 10 kHz. The gate is driven between -4 V and +15 V. It has already been determined that the device will remain within its safe operating area (SOA). We want to determine the maximum allowable heat sink thermal resistance, $R_{\theta SA}$, to maintain the junction at a conservative temperature of 125°C for an ambient temperature of 40°C.

The device dissipation has two parts: on-state and switching losses. Since they occur at different times during the pulse and are each short compared to a thermal time constant, they can be treated independently and their results added.

Energy is lost during the on-state at a power of $R_{DS(\text{on})} I_{DS}^2$. But $R_{DS(\text{on})}$ is a function of both junction temperature and drain current, so we must consult Fig. 25.9(a) which is taken from the device data sheet. The figure shows $R_{DS(\text{on})}$ at $I_{DS} = 35$ A at $T_j = 175°$C and 25°C. We interpolate $R_{DS(\text{on})}$ to a value of 121 mΩ at $T_j = 125°\text{C}$. The on-state power during a pulse is then

$$P_{\text{on}} = (35^2)(0.121) = 148\ \text{W} \tag{25.10}$$

The switching loss is determined from the loss vs I_{DS} curves using the data sheet graphs shown in Fig. 25.9(b). Switching loss is not a strong function of temperature, so the measurement condition of $T_j = 25°\text{C}$ instead of 125°C is relatively immaterial. The E_{total} curve at $I_{DS} = 35$ A gives $E_{\text{total}} \approx 2$ mJ/cycle. Since the switching times are on the order of 10's of ns for this device, the instantaneous switching power is very high, though the average power loss associated with switching is not.



(a) (b)

Figure 25.9 Specifications for the C3M0075120D SiC MOSFET: (a) $R_{DS(\text{on})}$ vs. temperature and I_{DS}; (b) switching loss vs. I_{DS}. (Used with permission of Wolfspeed, Inc.)

The transient thermal impedance Z_θ presented to the 10 µs, 0.1 duty ratio current pulses is given by Fig. 25.8 as approximately 0.12°C/W. But Z_θ for the very short (10's of ns) pulses of power during switching is not available from Fig. 25.8. The time scale of these switching power pulses is extremely short compared to both the available time constants of the system and of the on-state power pulses. We can estimate temperature rise by including the switching energy with the longer time scale of the on-state power pulses (as the on-state pulses are still very short compared to the known system time constants). Distributed over the $t_{\text{on}} = 10$ µs duration of the conduction period, the switching energy provides an additional equivalent on-state power of

$$P_{\text{sw,equiv}} = E_{\text{total}}/t_{\text{on}} = (2 \times 10^{-3})/(10 \times 10^{-6}) = 200\ \text{W} \tag{25.11}$$

Therefore we use $Z_{\theta jc}$ and $P_{\text{on}} + P_{\text{sw,equiv}}$ to determine the maximum T_C allowed to maintain $T_j < 125°\text{C}$:

$$\begin{aligned}\Delta T_{jc} &= Z_\theta(P_{\text{on}} + P_{\text{sw,equiv}}) = 0.12(148 + 200) = 41.8°\text{C}\\ T_C &\le 125 - 41.8 = 83.2°\text{C}\end{aligned}$$

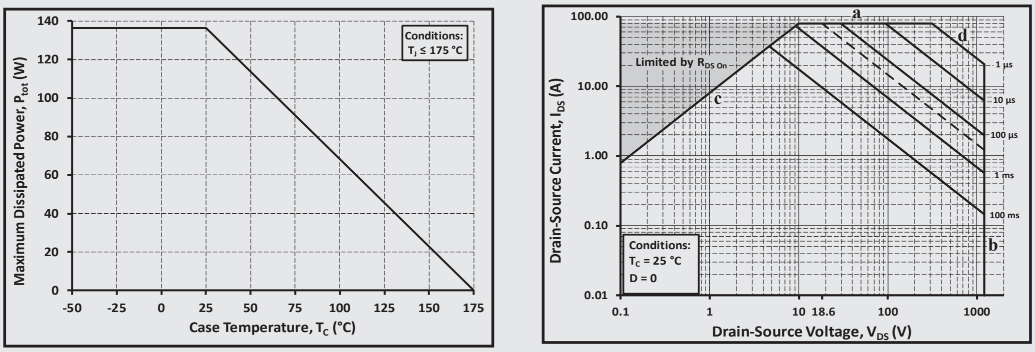
The thermal power transferred through the case to ambient includes both the conduction and switching loss. Since the case is thermally massive, it is considered an isotherm; and therefore we use the average total power to be dissipated to determine $R_{\theta CA}$. The average on-state loss is $\langle P_{\text{on}} + P_{\text{sw,equiv}}\rangle = 0.1 \times 348 = 34.8$ W. Using $\Delta T_{CA} = 83.2 - 40 = 43.2°\text{C}$, we can now calculate the maximum allowable heat sink thermal resistance $R_{\theta CA}$.

$$R_{\theta CA} \leq \frac{\Delta T_{CA}}{\langle P \rangle} = \frac{43.2}{34.8} = 1.24°\text{C/W} \tag{25.12}$$

Thermal resistance in this range is achievable with an appropriately specified extruded aluminum heat sink using natural convection.

Example 25.4 Derating the Safe Operating Area

A device's maximum allowed average power dissipation, $P_{D(\max)}$, is given in its data sheet but is usually specified at a case temperature $T_C = 25°$C, accompanied by a graph derating $P_{D(\max)}$ for higher values of T_C, as shown in Fig. 25.10 (a). The Safe Operating Area (SOA) graph provided in data sheets is derived from single pulse measurements (duty ratio $D = 0$) and also at $T_C = 25°$C with curves parametric in pulse width, as illustrated by Fig. 25.10(b). A case temperature of 25°C seldom conforms to the application, where the case temperature is generally much higher. So we need to modify the data sheet SOA to reflect our application, derating the device and producing a smaller SOA. The process requires the use of the P_D derating and transient thermal impedance curves from the data sheet, shown in Figs. 25.10 (a) and (b), respectively.



(a) (b)

Figure 25.10 SiC MOSFET C3M0075120D specifications: (a) maximum power dissipation derating curve; (b) the safe operating area, where the dashed line defines the boundary for a 100 μs pulse at $T_C = 100^o$C. (Used with permission of Wolfspeed, Inc.)

The maximum voltage and current constraints of the SOA are unchanged, as is the line constrained by $R_{DS(\text{on})}$. We need to determine new coordinates for the constant power constraints for the various pulse widths, at our application $T_C = T_{Ca}$, using the transient thermal impedance curves. The coordinates are scaled by δ_p, the ratio of $P(T_{ca})$, the maximum permissible average dissipation at T_{Ca}, to $P(25°)$, the allowable dissipation at $T_C = 25°$C, numbers obtained from Fig. 25.10(a).

We calculate the maximum allowable dissipation for our pulse if $T_j = 175°$C and $T_C = 25°$C, and scale it by the ratio δ_p to obtain $P_p(T_{Ca})$, the maximum pulsed power. This allowable dissipation at T_{Ca} then allows us to calculate new $V_{DS} - I_d$ coordinates on the SOA graph for our application case temperature and pulse width.

We illustrate the process by derating the iso-power line in Fig 25.10(b) for a 100 μs pulse at $T_{ca} = 100°$C. Figure 25.10(a) gives us $P(25°) = 136$ W, $P(100°) = 68$ W, and $\delta_p = 0.5$. From Fig. 25.8 for a single 100 μs pulse, we estimate $Z_\theta = 0.06°$C/W which we use to calculate $P_p(25°)$, the 100 μs pulse power if $T_C = 25°$C and $T_j = 175°$C, which we scale by δ_p to give us $P_p(100°)$.

$$P_p(25°) = \frac{175 - 25}{0.06} = 2917 \text{ W} \tag{25.13}$$

$$P_p(100°) = P_p(25°) \times \delta_p = 1488 \text{ W} \tag{25.14}$$

We can now calculate a pair of coordinates on the iso-power limit line for a 100 μs pulse with $T_C = 100°$C. Choosing $I_D = 80$ A (the maximum specified pulse current),

$$V_{DS} = \frac{P_p(100°)}{I_D} = \frac{1488}{80} = 18.6 \text{ V} \tag{25.15}$$

We now have one point on the line, but the line is iso-power with a slope of -1 so we can draw the new constraint on the SOA graph, as indicated by the dashed line in Fig. 25.10(b).

Notes and Bibliography

The volume of work published in the general area of heat transfer is massive. The references selected here are representative of those that are accessible to the nonspecialist. An undergraduate text covering most topics of interest to the designer of electronic equipment, although not in this context, is [1]. The book is liberally illustrated and contains numerous examples. Lienhard and Lienhard [2] is a very comprehensive text with numerous examples and problems addressed to juniors through graduate students. Among its unique inclusions are photographs of Ludwig Prandtl, Osborne Reynolds, and Ernst Kraft Wilhelm Nusselt, whose namesakes are the Prandtl, Reynolds, and Nusselt numbers, important parameters in heat transfer. It is inexpensive and available as an e-book.

Lee [3] is focused on specific heat exchange technologies. The book includes extensive analyses of the different devices used for heat transfer. Steinberg, [4], is short on theory but long on practical applications. The numerous examples reflect the author's own experience in the military/avionics area. A lot of practical data is presented, and there is a good discussion of fluid-based heat transfer systems, including heat pipes.

A concise discussion and mathematical statement of the Wiedman-Franz law can be found on p. 150 of Kittel, [5].

The TI application note [6] provides an extensive discussion of using thermal vias for heat sinking on printed circuit boards.

1. F. M. White, *Heat Transfer*, Addison-Wesley, 1984.
2. J. H. Lienhard IV and J. H. Lienhard V, *A Heat Transfer Textbook*, 5th ed. Dover Publications, 2019.
3. H. Lee, *Thermal Design: Heat Sinks, Thermoelectrics, Heat Pipes, Compact Heat Exchangers, and Solar Cells*, Wiley, 2010).
4. D. S. Steinberg, *Cooling Techniques for Electronic Equipment*, 2nd ed. Wiley Interscience, 1991.
5. C. Kittel, *Introduction to Solid State Physics*, 6th ed. New York: Wiley , 1986.

6. Texas Instruments, *ANM-2020 Thermal Design By Insight, Not Hindsight*, Application Report SNVA419C-April 2010- Revised April 2013.

PROBLEMS

25.1 A double-insulated window is made of panes of glass 4 mm thick spaced 1 cm apart. Window glass has approximately the same thermal resistivity as SiO_2, 100°C-cm/ W. If the interior temperature of the building is 25°C and the outside temperature is 0°C, what is the rate of heat lost by conduction in kW/m^2?

25.2 The CRC *Handbook of Chemistry and Physics* (35th ed.) defines thermal conductivity of materials as "the quantity of heat in calories which is transmitted per second through a plate 1 cm thick across an area of 1 cm^2 when the temperature difference is 1°C." The value for dry compact snow is 0.00051. What is the thermal resistivity of dry compact snow in units of °C-cm / W?

25.3 An isolating interface of alumina having a thickness of 1 mm is placed between the device package and the heat sink in Fig. 25.3 (Example 25.2). What is the junction temperature T_j, if other parameters of the example remain unchanged?

25.4 Figure 25.11 shows two identical devices, Q_1 and Q_2, mounted on a common heat sink. The devices are in TO-220 packages and have a thermal resistance from junction to case of $R_{\theta jC} = 1.2$°C/ W. The interface between the case and sink has a thermal resistance of $R_{\theta CS} =$ 0.20°C/ W, and the thermal resistance between the sink and ambient is $R_{\theta SA} = 0.8$°C/ W.

(a) Draw the static thermal model for the thermal system of Fig. 25.11.

(b) If the devices are dissipating the same power, and $T_A = 40$°C, what is the maximum total power that can be dissipated if $T_{j(\max)} = 150$°C?

(c) What is the maximum possible power dissipated if only one of the devices is operating?

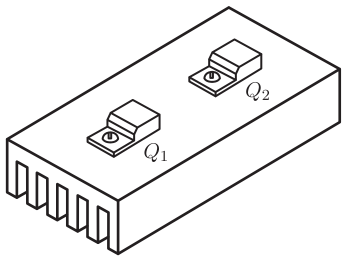


Figure 25.11 Two devices mounted on a common heat sink analyzed in Problem 25.4

25.5 A transistor in a TO-3 case has a junction-to-case thermal resistance of 1°C/ W and is to be used in an environment having an ambient temperature of 60°C. The transistor is to be isolated from its heat sink by a Mylar spacer having a thickness of 0.1 mm, and the available heat sink has a specified value of sink-to-ambient thermal resistance of $R_{\theta SA} = 2$°C/ W.

(a) Determine and draw the static thermal model for this system.

(b) What is the maximum power that can be dissipated by the device if its junction temperature must be less than 150°C?

25.6 Figure 25.12 shows the internal structure and dimensions of a power diode mounted in an axial lead package. The diode is cooled by conduction through its leads, which are soldered to terminals that are assumed to be at temperature T_A. Heat is generated at the junction of the diode, which is planar and centered between the two surfaces.

(a) Draw the analog circuit model for the thermal system of Fig. 25.12.

(b) If the maximum permissible junction temperature of the diode is $T_j = 225°\text{C}$, what is the maximum permissible dissipation for $T_A = 75°\text{C}$?

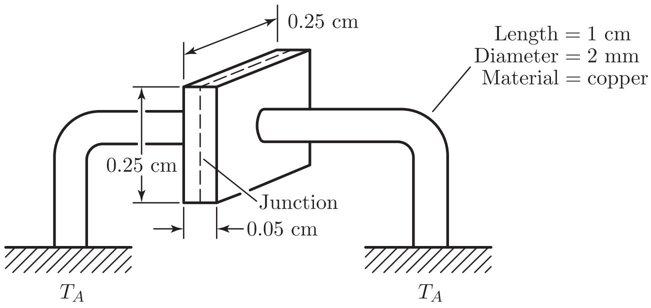


Figure 25.12 The axial lead packaged diode analyzed in Problem 25.6.

25.7 A superjunction MOSFET in a TO-247 package is mounted to a heatsink with a 0.5 mm thick silicone pad as the interface. The thermal contact area of a TO-247 package is 2.5 cm^2.

(a) At the mounting pressure of 10 psi the pad has a thermal impedance, Z_{th}, of 0.6°C-cm^2/W. What is $R_{\theta CS}$, the case to sink thermal resistance?

(b) The junction to case thermal resistance of the MOSFET is $R_{\theta jC} = 0.3°\text{C/W}$ and at a junction temperature T_j of 150°C its on-state resistance, $R_{DS(\text{on})} = 40\ \text{m}\Omega$. If the heatsink temperature can be maintained at 50°C, what is the maximum continuous current that the device can conduct?

25.8 What is T_f in Fig. 25.6(d)?

25.9 The SiC MOSFET characterized by the transient thermal impedance curves of Fig. 25.8 is subjected to an overload condition that is cleared by a protection circuit in 3 μs. The MOSFET had been operating at a junction temperature of $T_j = 150°\text{C}$. How much energy can the device be allowed to dissipate during the fault to maintain $T_j \leq 200°\text{C}$?

25.10 Consider the "single pulse" thermal response of a system (e.g., as illustrated in Fig. 25.8). This response $Z_\theta(t)$ is in fact the thermal step response of the system. That is, $Z_\theta(t)$ represents the temperature rise response over time to a unit step in input power at $t = 0$.

(a) Show that if one can treat the dynamic thermal system as a linear, time-invariant (LTI) system (e.g., the circuit elements in the model of Fig. 25.6(b) are LTI), then we can write the temperature response to a short pulse in power of amplitude P starting at $t = 0$ and having duration t_1 as:

$$\Delta T_{jC} = P[Z_\theta(t) - Z_\theta(t - t_1)]$$

(b) For the same LTI system assumption, what would be the temperature rise response to a sequence of two pulses of amplitude P, each of duration t1, one starting at $t = 0$ and the second starting at $t = t_2 (> t_1)$?

25.11 Using the CREE SiC SOA of Fig. 25.10(b), determine the derated limiting boundary for a 1 ms pulse if the case temperature is 125°C. What is the maximum allowable I_D?