THERMAL ANALYSIS OF SEMICONDUCTOR SYSTEMS

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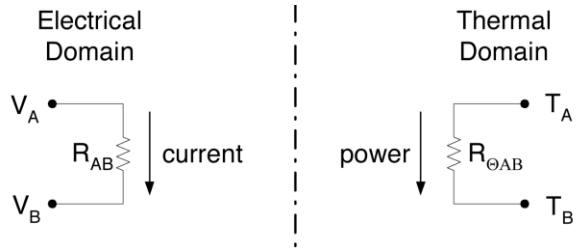
Abstract- **Designing a cost competitive power electronics system requires careful consideration of the thermal domain as well as the electrical domain. Similarly, over designing the system adds unnecessary cost and weight; under designing the system may lead to overheating and even system failure. Finding an optimized solution requires a good understanding of how to predict the operating temperatures of the system's power components and how the heat generated by those components affects neighboring devices, such as capacitors and microcontrollers. No single thermal analysis tool or technique works best in all situations. Good thermal assessments require a combination of analytical calculations using thermal specifications, empirical analysis and thermal modeling. The art of thermal analysis involves using all available tools to support each other and validate their conclusions. This paper first presents the basic principles of thermal systems and then describes some of the techniques and tools needed to**
complete such an analysis. Power devices and low lead count packages are the primary focus, but the concepts herein are general and can be applied to lower power components and higher lead count devices such as microcontrollers.

Index Terms- **Die-attach performance, Raman - Thermography, FEA**

I. INTRODUCTION

The basic principles of thermal analysis are similar to those in the electrical domain. Understanding one domain simplifies the task of becoming proficient in the other. This is especially clear when we consider thermal conduction. The two other thermal transport mechanisms are discussed later. Each domain has a "through" and an "across" variable.The variable can be thought of as the
parameter that flows from one reference point to another. Current is the variable for the electrical domain and power is the through variable in the thermal domain.
The across variable can be thought of as the variable that forces the flow of current or heat. In each domain the forcing function is a difference in potential; in one domain it's temperature and in the other it's voltage. Both systems have a resistance that impedes the flow of the through variable. Given the duality of the two systems, it is no surprise that the fundamental equations of the domains are similar.The white paper describes about convection and radiation , thermal responses,thermal modeling and empirical measurements and thermal modeling software.

FIG 1:- FUNDAMENTALS RELATIONSHIPS IN THE THERMAL AND ELECTRICAL DOMAINS



1.1 TRANSIENT THERMAL RESPONSE

The duality extends to transient as well as steady state conditions. The existence of capacitance in both domains results in thermal RC responses like those we are familiar with in the electrical domain.
Thermal time constant is equal to the thermal R-C product, that is:

tQ = RQ CQ (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:

CQ= q t/ΔT (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:

CQ= 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:

ΔT(AB) = R(QAB) P(D) (1 - e(-t/t))
(Eq. 5)

II. CONVECTION AND RADIATION

Conduction is only one of three possible thermal transport mechanisms. In addition to conduction, the other mechanisms are radiation and convection. In fact, these other transport mechanisms often become the predominant ones as heat exits a module. Radiation and convection are clearly more complex thermal transport mechanisms than conduction, and we will see that in their governing
equations. Consider first convection, which occurs when a solid surface is in contact with a gas or liquid at a different temperature. The fluid's viscosity, buoyancy, specific heat and density affect the heat transfer rate from the solid's surface to the fluid. The surface's area and its orientation (i.e., horizontal or vertical) as well as the shape of the volume in which the fluid is free to circulate are additional factors. And, having the greatest effect is whether the system uses forced air (fan cooling) or natural convection. Although convective behavior is quite complex, its descriptive equation is relatively simple and can be expressed as:
q = k A ΔT
(Eq. 6)
where:
q = heat transferred per unit time (J/s)
k (or h) = convective heat transfer coefficient of the process
(W m-2 .C-1)
A = heat transfer area of the surface (m2)
ΔT = temperature difference between the surface and the bulk
fluid (.C)
The convection coefficient, k, can be determined empirically, or it can be derived from some thermal modeling programs. It changes, for example, with air speed when a fan is used, with module orientation or with fluid viscosity. Radiation is a completely different process and augments the other two transport mechanisms. Quantifying heat transferred by radiation is complicated by the fact that a surface receives as well as emits radiated heat from its environment. "Gray Body" (vs. "Black Body") radiation is the more general condition and its governing formula is:
q = e s A (Th4 - Tc4)
(Eq. 7)
where:
q = heat transfer per unit time (W)
e = emissivity of the object (one for a black body)
s = Stefan-Boltzmann constant = 5.6703*10-8 (W m-2 K-4)
A = area of the object (m2)
Th= hot body absolute temperature (K)
Tc= cold surroundings absolute temperature (K)
Exercising Equation 7 shows that for geometries and temperatures typical of semiconductor packages, radiation is not a primary transport mechanism. But at the module level, because of the much larger surface area and the heat transfer's dependence on the 4th power of temperature, radiation can play a much more important role. Nevertheless, for larger objects thermal radiation is often accounted for by including its effect in a general thermal resistance value. But since radiation is a strong function of temperature, this practice is acceptable only over a modest range of module and ambient temperatures or when the module and ambient temperatures are nearly the same. Applying three different and sometimes complex thermal transport mechanisms to a complex thermal circuit creates a system that cannot be evaluated by simple and inexpensive tools. Often the only feasible
approach is to model a thermal circuit with tools created for that purpose and validate that model with empirical testing.

III. DIFFRENCES BETWEEN ELECTRICAL AND THERMAL DOMAINS

1. The electrical and thermal domains differ is a good way to avoid some common misconceptions and misunderstandings. One key difference between the domains is that in the electrical domain the current is constrained to flow within specific circuit elements, whereas in the thermal domain heat flow is more diffuse, emanating from the heat source in three dimensions by any or all of the three thermal transport mechanisms. In electrical circuit analysis current is limited to defined current paths

and that allows us to use lumped circuit elements, such as resistors, capacitors, etc. But in the thermal domain the thermal path is not so constrained, so using lumped elements is not as appropriate. Even in relatively simple mechanical systems, defining lumped thermal components is often an exercise in estimation, intuition and tradeoffs. We want to use lumped elements to model our thermal systems, but we must remember that to do so we've made many simplifying assumptions.

2. A second major difference is that coupling between elements is usually a more prominent behavior in the thermal domain. Isolating devices in electrical circuits is usually easier than isolating elements in thermal networks. Therefore, good thermal models usually employ thermal coupling elements, while many electrical circuits do not require them. The tools to model complex systems are quite different between the domains. Electrical circuit analysis tools, such as SPICE, can be used for thermal circuits of lumped elements, but such tools are not appropriate for assessing how heat flows in a complex mechanical assembly. The test and evaluation tools differ as well. You can't clamp a "heat flux meter" around a thermal element to monitor how much power passes through it. For thermal analysis infrared cameras and thermocouples replace oscilloscopes and voltage probes. Even though the domains have their differences, they are likely to be interdependent. A prime example is the temperature dependence of a power MOSFET's on-resistance, which increases by 70 to 100 percent as the temperature increases from 25.C to 150.C. The higher on-resistance increases power dissipation, which elevates temperature, which increases on-resistance, and so on.

IV. THERMAL MODELING AND EMPIRICAL MEASUREMENTS

1. To construct the baseline thermal model for a given process, an electrical simulation of the GaN device using non-linear models for the field effect transistors is used to obtain estimates of heat generation which allow for an initial prediction of thermal performance. The device is then physically fabricated is tested.
2. Empirical thermal data is collected with both electrical measurements and micro-Raman measurements. Raman thermography is a non-invasive optical technique, based on Raman scattering spectroscopy, that enables temperature measurements with sub-micron spatial and nanosecond time resolution.1 It probes the temperature-induced phonon shift in a material, with respect to a reference phonon frequency measured at ambient temperature.2
3. Raman thermography has been established as an important high fidelity regimen for physically small geometries. It offers proven, accurate and repeatable improvement in spatial resolution down to 0.5μm as well as micron scale depth resolution for true 3D thermography. As will be discussed below, Raman thermography improves upon the underestimation of device peak temperature due to lateral spatial averaging associated with conventional infrared (IR) thermography measurements.
4. A combination of measurement methods, including micro-Raman and electrical, should be used in conjunction with thermal simulations, in order to gain accurate information on the thermal properties of GaN devices.

4.1 THERMAL ANALYSIS

Once the baseline thermal model development is complete, FEA is then employed to accurately predict channel temperature and thermal resistances at the product level. The FEA begins with a die-level simulation, proceeds to the package level, and continues all the way to system level, where it examines the packaged product within the next higher assembly.

When modeling and measuring heat generation and removal, it is critical to select proper boundary conditions and to understand the impact of those assumptions. Commonly, unrealistic or improper assumptions are made on temperature and heat removal boundary conditions. The unrealistic predictions and measurements that result often lead to product designs that appear to work well on a datasheet, but will fail in application.

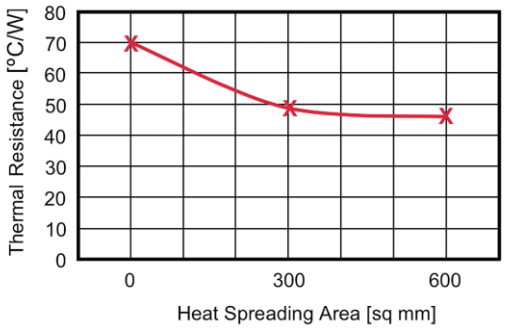
4.2 THERMAL RATINGS

1. Thermal Resistance Ratings

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

resistivity and the wire bonds' very small cross sectional area. The portion of the lead frame on which the die is placed is called the "die paddle," or "flag." The package's thermal performance can be enhanced substantially by improving the thermal path from the paddle to the package's surface. One way to do this is to stamp the lead frame so that some of the leads are directly connected to the die paddle (flag). This allows heat to flow relatively unimpeded through the "thermally enhanced" leads and onto the PCB. Another approach is to expose the die paddle at the bottom (or top) of the package. This structure yields a much more direct thermal path and vastly improves the device's thermal performance. Since the primary thermal path differs with modifications in the package construction, each variation merits its own thermal reference points and, therefore, its unique thermal resistance specifications. Table 2 contains thermal resistance ratings of two devices with essentially the same die. Both use a version of the 32-lead, fine-pitch, wide-body SOIC. One version has an enhanced lead frame (the two centermost leads on each side of the package are directly connected to the die pad), and the other has an exposed pad on the IC's.

FIG 2:- THERMAL RESISTANCE DECREASES WITH THERMAL PAD AREA



2. Die-attach performance as a factor in device operating temperature

One of the challenges of thermal modeling is finding an accurate estimate for die-attach thermal performance, which is a very important factor in device operating temperatures.

Vendors of die-attach solders/epoxies often only list the bulk thermal conductivity (k) of their product. This is only one component of the overall die-attach thermal impedance. Bondline thickness, interfacial resistances, voiding, and filler characteristics all contribute to the overall thermal resistance, and these are to a large extent dependent on dispensing and curing processes. In addition, die-attach integrity and performance are impacted by material properties and surface characteristics of the two items being bonded. Experimentation is usually required to know with reasonable certainty how a die-attach solution will perform.

The graphic below illustrates the relationship between bondline thickness, bulk thermal conductivity, and total die-attach thermal resistance.

FIG 3:-DIE ATTACH THERMAL RESISTANCE

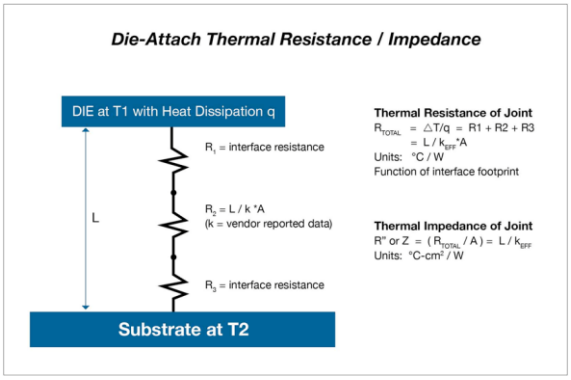
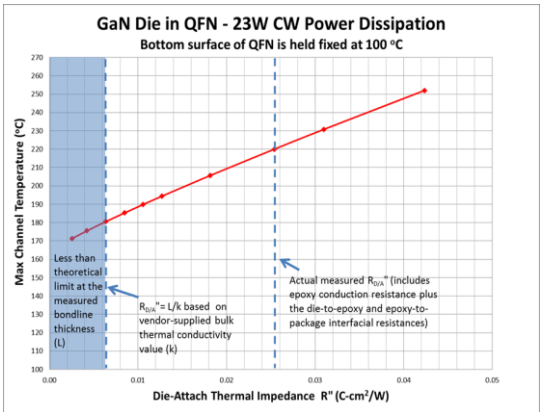


FIG 4:-GaN-23W CW POWER DISSIPATION



3.Transient Thermal Response Ratings

In many systems the worst case conditions occur during a transient condition, such as when inrush current flows into a cold lamp filament, startup or stall currents appear in a motor or a short circuit causes fault current. The duration of such a transient could very well be far shorter than the system's thermal time constant, especially since we often use intelligent power devices to manage such events. If the system is designed to meet worst case transient conditions for an unnecessarily

long time, the system will be over designed. Knowing how the system responds to thermal transients helps the designer size components and provide adequate, but not unnecessary, heat-sinking. When you include characterization in the time

domain to the many possible ways to characterize a device in steady state, the possible options are too large to manage. To provide the most universally
useful data, the industry has adopted and promoted a concept called "transient thermal response." Transient thermal response is a device's or a system's thermal
response to a step input of power. Note that the step input starts at zero power, steps to some amplitude, then remains at that amplitude forever. A transient thermal response curve is a plot of the junction temperature rise as a function of time. As such, the curve incorporates the thermal effects of a device's entire structure. Manufacturers usually create these curves empirically, but they can create them with models as well. Each point on the curve shows the die's maximum temperature versus how long the power pulse has been present. Transient response curves can be referenced to case or ambient temperature. It is important to note that the specific shape of the power pulse used in the characterization may not match the shape of the pulse of interest in the application. Therefore, it is important to remember what the thermal response curves represent and to use them accordingly.

4.3 THERMAL MODELLING 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.

V. CONCLUSIONS

Worst case conditions are often briefer than the module's thermal time constant. Upon a change in operating conditions, a module can easily take more than 10 minutes to stabilize thermally. The system may be able to store the energy from the worst case conditions in the module's thermal capacitance. Heat sinks, heavy copper and multi-layered
boards all add to the module's thermal capacitance. Remember, too, that even when a device is mounted to a worst case board, the device itself has some ability to absorb energy. If a device has fast fault detection circuitry, it may be able to absorb the energy and manage the fault without harm to the device, the PCB or the load. Because we have a limited innate ability to sense thermal phenomena, we lack an intuitive feel for how thermal systems behave. This makes it advisable to monitor temperature at many points on a PCB or, better yet, photograph the module, its PCB, and its harness with an infrared camera. Any unexpected temperatures you find point you to aspects of the thermal circuit that you do not completely understand. Finding these surprises provides valuable clues that can lead to a better understanding of the module's thermal behavior.

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