1. Introduction

Most of thermal engineers or designers are using simplified thermal resistance model such as block model, 2R thermal model or Delphi model etc., which cannot be used to describe 3D heat distribution in physical device therefore its accuracy is limited. Thermal structure function is a proven methodology to do experiment based structural analysis of heat path inside electronics package or cooling devices, but the problem is that structure function represents 3D thermal distribution by 1D Rth-Cth ladder model which is hard to understand, especially for those mechanical engineers or researchers who has strong imagination in terms of “geometry” or “shape,” but such concept does match the spatial distribution in most of the cases.

In thermal engineering world, actually most of the people have stronger mechanical background, this is why they prefer “shape” based block model or 2Rth model with poorer accuracy. If thermal design margin is enough to cover the lack of accuracy in the model, 2Rth, even block model is easier to use, but unfortunately thermal design margin is getting smaller in the industry trend and this makes more advanced thermal model necessary.

This article gives the idea of how to use isothermal surface to read structure function and how to connect 1D Rth-Cth ladder model to 3D heat spreading path so that structure function can be accepted easier.

2. Understand the Challenge of Thermal Analysis in Real World

The best way to study thermal structure is taking a look at the isothermal distribution or heat flux distribution along the heat-spread path. However, in the real world it is impossible to take a picture of heat distribution inside any solid object as we do in a CDF software simulator. In this article CFD simulator is used to illustrate heat distribution to help understanding in a easier way. (All simulations in this article are done in FloTHERM 9.2.)

According to the structure function theory,[1] thermal systems are distributed RC systems which can be modelled by thermal resistance Rth and thermal capacitance Cth. To evaluate a RC system, the most common way is to measure transient response under step power excitation.

Consider the simulation setup in Fig. 1. Heat source (10 mm × 10 mm square in YZ plane) locates at the left side of X axis; Heat conductive material is of the same size in YZ

Fig. 1  Experiment setup overview.
plane as heat source and extends from heat source to cold-plate along X axis. Length of the material (heat source to coldplate in X axis) is 30 mm. Ideal heat insulation material is attached to the material to prevent heat from escaping to Y and Z direction. The cold plate at the right side of X axis provides an ideal thermal boundary condition of fixed 25 degC. In such setup the heat flux will be constrained to X axis which is a one dimensional heat spreading path starting from the heat source on the left side to the cold plate on the right side along X axis as shown in Fig. 2.

Since thermal property Rth and Cth of the material on the heat spreading path determines step power response of the system, theoretically we can evaluate the thermal structure by measuring the thermal transient response in an electrical test method as standardized in JEDEC JESD 51-1 in 1995.

In the real world there is neither “ideal” heat insulator nor “ideal” cold plate to help us constructing an ideal 1D heat path for demonstration. Because this is an instructive article to help understanding, we do thermal transient simulation in CFD simulator FloTHERM to obtain transient result instead of building a physical experiment environment to measure. In the practical cases, thermal transient tester such as T3Ster is capable of measuring thermal transient result and outputing structure function, such examples are discussed in another paper.[2]

In the simulation, we place a flag material in the middle of pure copper to study the thermal transient response “Temperature vs Time.” Three transient curves are obtained by changing the flag material thermal property.
1. Same as pure copper. (Cu50W)
2. Douled specific heat against pure copper. (Cu50W_2xCth)
3. Halved thermal conductivity against copper. (Cu50W_2xRth)

Figure 3 plots three step power responses together, in which we can see the curves are different.
- “2xCth” system has larger thermal capacitance than the original one because the curve changes slower
- “2xRth” system has larger thermal resistance than the original one because the curve has larger temperature lift.

If such “general” conclusion is enough, then temperature v.s. time step power response is quite enough, but for thermal designer, especially structure designer such result is obviously inadequate. So we need to find out a way to analyze the thermal spatial structure.

3. From 1D Structure Function to 3D Thermal Distribution

Structure function was introduced decades ago. It is a mathematical conversion from time domain step power response to Cth-Rth domain. In the time domain the structural thermal properties are all included but too abstract for human to understand. Converting step power response to Cth-Rth domain structure function helps human brain to understand what is exactly happening inside the heat spreading path.

Figure 4 is the structure function converted from step power response in Fig. 3 (refer to [1] for the structure function calculation theory). In this plot we can see a very clear diverging point locating at Rth=1.4 k/W Cth=1.93 J/K. Since the original of these values are from thermal transient responses, we note them as “experimental values” though the “experiment” is done by transient simulation in CDF software.

On the other hand, we can also calculate “numerical value” in the following mathematical way.
Rth = \( \frac{L}{A \times \lambda} \)  
Cth = \( V \times D \times S \)

L: distance along heat flux direction.
\( \lambda \): Thermal conductivity.
A: cross section size.
V: volume
D: density
S: specific heat

Using the properties in Table 1 we can get numerical value of the copper block on the left side Rth\(_{\text{copper-left}}\) = 1.4 K/W and Cth\(_{\text{copper-left}}\) = 1.93 J/K which is just where we observed the diverging point on structure function in Fig. 4. The material next to the first copper block is our flag material, we can see that the changes we make to flag material does not affect structure function from Rth=0 to 1.4 K/W, and in this section structure function is a straight line which is due to the constant material property in the first copper block.

If consider the whole heat flux, because it always spread from one isothermal surface towards next isothermal surface, in this 1D situation isothermal surface extends X axis. In some aspects the heat spreading path is constructed by a series of isothermal surface, it is a very effective way to study thermal structure by inspecting the distribution of isothermal surface. In the 3D isothermal view in Fig. 5 we find out 0.14 k/W isothermal surface is just the same size and shape as the first copper block. At this point, we know structure function can be used to evaluate the material thermal properties and the spatial thermal distribution.

Next, let us take a look at the slope of the structure function as shown in Fig. 6.

In the original curve “Cu50W,” the structure function is a straight line. The constant slope suggests the material property is constant along the heat spreading path dovetailing with the experiment.

In the 2xCth curve, we can identify a double slop section starting from diverging point at 0.14 K/W ending at 0.26 K/W, this is because we set double specific heat to the flag material which introduces doubled thermal capacitance. After 0.26 K/W, the 2xCth curve go back parallelly against the original one, because there is pure copper again after flag material section.

To confirm the theory, let us take a look at the 2xRth curve. In the setup, thermal conductivity of the flag material is halved against pure copper, if we calculate in a numerical way we know there must be doubled thermal resistance in the flag section of the structure, since the specific heat remains the same as pure copper there must be a “half slope” section in structure function. In the experimental result, we can really identify this half slope section as shown in Fig. 6.

From this experiment, we understand there is relationship between structure function and the spatial heat spreading distribution, and the bridge will be isothermal surface.

### 4. The Structure Function of 3D Heat Flow

The previous experiment is done in a 1D heat flow setup which is too ideal from reality. In this section, we are going to see what happens in a 3D heat flow structure.

Figure 7 shows the experiment setup which is very close to a real semiconductor package and board situation where: heat source is on the upper surface of silicon chip which is attached to a metal (copper) substrate and then attached to a FR4 board. Every material is built as a cubic block and contact thermal resistance is NOT considered for simplicity.

The heat flow shown in Fig. 8 three dimensionally
spreads towards atmosphere which is fixed to 35 degC. In heat flux view in Fig. 9 we can see that inside chip it is almost a top-down 1D path, but as soon as heat goes in to copper spreader the heating power spreads all directions in the copper which is a 3D structure.

In structure function we can see a straight line section from 0~0.4 K/W at the beginning. This straight line comes from the nearly 1D heat flow inside chip. When heat conducts from chip upper surface to lower end, air outside chip has relative huge thermal resistance compared to silicon, this forces heat go just along the chip thickness direction the same as we discussed in the previous section. The thermal capacitance corresponding to chip is 0.0018 J/K @ 0.4 K/W which is a little larger than chip thermal capacitance because some boundary lay between chip and air are included. To verify the structure function we will check the isothermal surface again in CFD software as shown in Fig. 9. In Fig. 9 the isothermal surface 0.4 K/W is almost the same size and shape as silicon chip.

However, after heat conduction break into copper frame area, structure function changes to a curve as shown in Fig. 10.

From 0.6 K/W~0.8 K/W of measured structure function, the dominant heat spreading path is inside copper spreader. In this setup copper spreader has much larger size than chip, unlike in chip area there is air-block heat is able to spread not only in thickness direction but also in latitude direction. Here we visualize the heat conduction from 0.4~0.8K/W as shown in Fig. 11. We can observe that isothermal surface is getting larger exponentially inside the copper block, this 3D heat spreading makes slope of structure function increasing.

For the same reason, structure function from 0.8 K/W~1.2 K/W also indicates heat spreading in the copper block, and the structure function curve shows increasing slope so far, but after 1.2 K/W we observer decrease slope curve as shown in Fig. 12.

To understand this decrease inflexion point at 1.2 K/W in structure function, let us take a look at this isothermal face.

We can see in Fig. 13 the isothermal surface is “trimmed” at the physical copper boundary. Due to this physical limitation in copper volume, structure function decreases. The exact flexion point must where isothermal surface first strike physical copper boundary which is...
Figure 14–Figure 17 illustrate how heat spread from 1.0 K/W to 10 K/W. We can now give the conclusion:

- **1.0 K/W–1.2 K/W**, heat starts to spread in FR4, but radical 2D spreading in copper block is dominant. This causes structure function to increase.
- **1.2 K/W–3.0 K/W**, heat spreads in both copper and FR4, but the dominant path changes from copper to FR4 gradually. This is why structure function slope decreases in this section.
- **3.0 K/W–5.3 K/W**, heat spreads in a 3D way in FR4 dominantly. This causes structure function slope to increase in this section.
- **5.3 K/W–10 K/W**, heat spreads in FR4 changes from 3D to a 2D radical ways due to the limited FR4 board thickness. This causes structure function slope to decrease.
- **After 10 K/W**, heat spreads both in FR4 and fluid air, but “weight” of fluid air becomes dominant so structure function increases very rapidly.

Figure 18 gives the overview of the structure function from 0–20 K/W.
5. Conclusions

Traditionally when doing thermal structural analysis, we used to build thermal model in CFD simulation software. The challenge in CFD software is how to verify model correctness, which is also the most serious problem for CFD engineer.

Because structure function can be obtained from both experimental way and simulation way, we are now able to verify package thermal model against real package by comparing their structure function. If there is any mismatch in the model, we can easily find out the problem in the model and make sure CFD software generates accurate result.

References


Yafei Luo was born in 1980, China. Graduated from Peking University with bachelor degree of physics in 2003 and obtained master degree of Computer Science in Florida International University in 2005. He has 5 years experience of ASIC design/verification and now his work is focusing on thermal measurement and analysis as senior application engineer in Mentor Graphics Japan Co., Ltd.