Structure Functions – The Bridge Between Thermal Measurement and Thermal Simulation

TRADITIONALLY thermal measurements of electronic components have been done using thermocouples. However, thermocouples come with critical disadvantages, (such as contact thermal resistance between target and probe which makes the measured result very unstable, and the tendency of the thermocouple to conduct heat away from the surface being measured) making them near useless for measuring the surface temperature of plastic packages.

Increasingly there is a need to validate thermal models during product design to ensure that the product will perform as designed, by confirming material properties and the thickness of thermal interface material (TIM) layers. A major issue with thermocouples is that they simply cannot measure the temperature of the internal structure. Yet by design, the dominant heat flow path is from the junction, through many materials and material interfaces before passing into a PCB or heatsink, whose temperature can be conveniently measured. Even then, a thermocouple only provides a single temperature value. Thermocouples are therefore a 'blunt instrument' when it comes to thermal design verification.

In this article, we are going to introduce the thermal structural analysis method, which is based on transient thermal measurements, that allow the thermal behavior of the system, including heat spreading, to be characterized as a distributed Resistance-Capacitance (RC) network. By measuring the transient response of junction, we can easily observe the heat spreading path inside package, board, TIM and heat-sink, etc.

The Challenge of Thermal Analysis in the Real World

The best way to study thermal structure is to take 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. The only way to inspect heat flux distribution vitually is by using a software simulator such as FloTHERM™ used in this article.

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

Consider the experiment setup in Fig 1. Ideal heat insulation material prevents heat from escaping to Y and Z direction, the cold plate at the right side of X axis provides an ideal thermal boundary condition. In this setup heat flux will be constrained to X axis which can be considered as one-dimentional heat spreading path starting from the heat source on the left side to the cold plate on the right side along X axis.

Thermal property Rth and Cth 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 experiment, we place three kinds of flag material in the middle of heat path.

1. Same as pure copper. (Cu50W)
2. Doubled specific heat against pure copper (Cu50W_2xCth)
3. Halved thermal conductivity against copper. (Cu50W_2xRth)

Figure 2 plots step power responses and Structure Function. In temperature response view, variation caused by different flag material can be seen, however it is not clear enough while in the Structure Function view the structural information can be clearly identified as shown in Figure 3.

Case Study Closer to a Real PCB Board Application

In a real-world application such as a package mounted on PCB board, heat spreads not only vertically but also horizontally as shown in Figure 4.

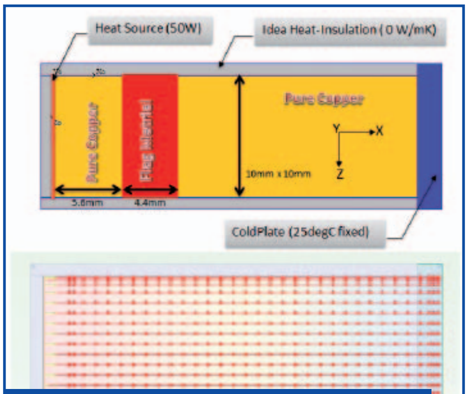

Figure 1. Experiment setup and heat flux view

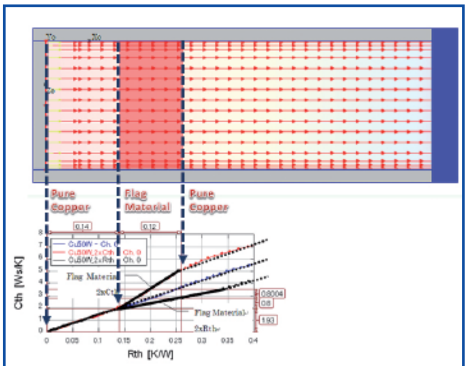

Figure 3. Rth in structure function increases along heat path

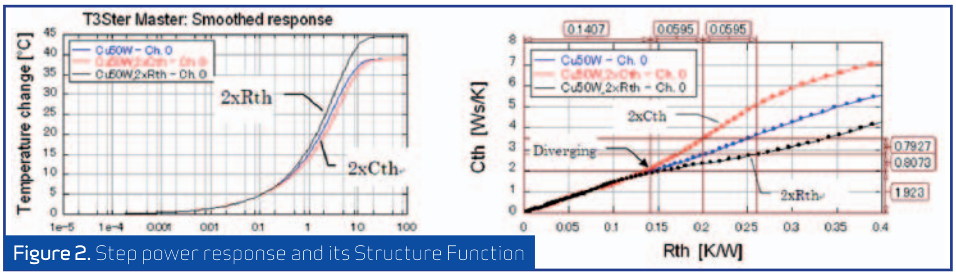

Figure 2. Step power response and its Structure Function

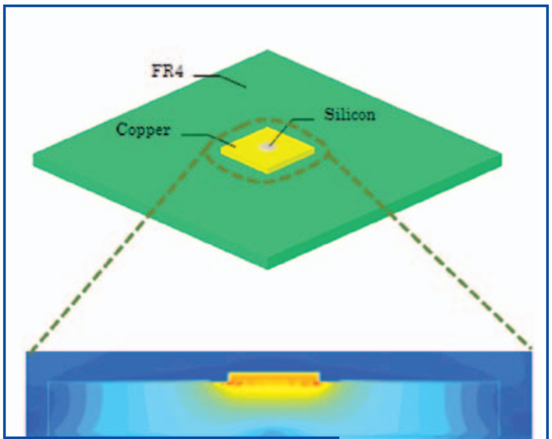

Figure 4. Heat flux inside a package

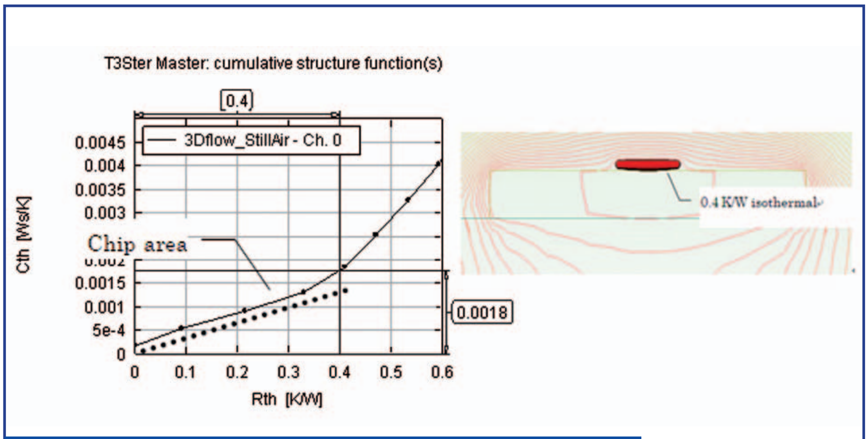

Figure 5. Structure function at its related 0.4 K/W isothermal surface

The heat source (silicon chip) is attached to a metal (copper) substrate and then attached to the FR4 board. Every material is built as a cuboid block and contact thermal resistances are not included for simplicity.

In the Structure Function, a straight line section from 0 - 0.4 K/W can be seen at the beginning. This straight line comes from the nearly 1D heat flow inside the chip as shown in Figure 5. This is because air outside the silicon chip has relatively huge thermal resistance compared to silicon, so that heat is forced to go through the thickness of the chip as discussed in the previous section. After 0.4K/W, structure function curve goes up exponentially which is caused by the 3D heat spreading in the metal substrate as shown in Figure 6.

For the same reason, Structure Function from 0.8K/W - 1.2 K/W also indicates heat spreading in the copper block and the Structure Function curve shows an increasing slope. After 1.2K/W we observe a decrease in the slope of the curve. This is caused by the physical boundary of metal substrate.

Conclusions

Traditionally when doing thermal analysis, thermal models built in CFD simulation software contain many thousands of pieces of data. The challenge for the user is how to verify the correctness of the model. As Structure Functions can be obtained from both experiment and simulation, we are now able to verify package thermal models against the data for real packages by comparing their structure functions. If there is any mismatch we can easily identify and resolve the problem, thereby increasing the fidelity of any board or system-level models in which the package model is used [2]. As Structure Functions track the heat flow path from the die junction to the ultimate ambient, the technique can also be applied to board and system-level models in late design to qualify electronics products before they go into full production.

Note

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References

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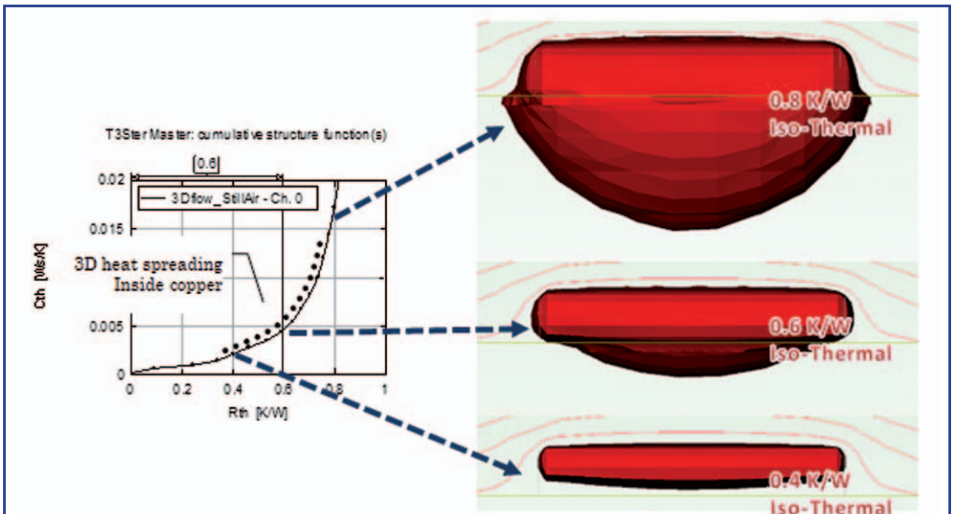

Figure 6. 3D heat spreading in the metal substrate layer