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Real-time imaging of temperature distribution inside a power device under a power cycling test

A. Watanabe *, R. Nagao, I. Omura

Department of Electrical Engineering/Electronics, Kyushu Institute of Technology, 1-1 Sensui, Tobata, Kitakyushu, 804-8550, Japan

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ABSTRACT

The analysis of temperature distribution in a power device package is essential to increase the reliability of power devices, because the temperature swing during the operation creates mechanical stress at the interfaces between these materials. However, the temperature distribution is difficult to obtain under operating conditions because of the limitation in the use of non-destructive methods to measure the inside temperature of the device. In this paper, we propose a method of real-time imaging of temperature distribution inside a DUT. This method is based on a "real-time simulation". The real-time simulation was realized by combining surface temperature monitoring and high-speed thermal simulation. The thermal simulator calculates temperature distribution inside the package by using the monitored surface temperature as a parameter. We demonstrate our system with a TO-220 package device under a power cycling test. The system indicated a temperature distribution change in the package with a frame rate of less than 1 s and the temperature difference at the Si chip was within 2 °C by a comparison with that estimated from forward voltage drop.

1. Introduction and concept proposal

A power device is constructed by the combination of certain materials with different coefficients of thermal expansion. The temperature swing during the device operation creates mechanical stress at the interfaces between these materials. Therefore, the analysis of temperature distribution in a power device package is essential to increase the reliability of power devices [1–5].

Some temperature sensors, for example a thermocouple and an infrared camera, are typically used to measure temperature distribution. Once these techniques are applied to a power device package, decapsulation cannot be avoided because these techniques measure only the surface temperature of materials. On the other hand, a thermal simulation numerically enables temperature analysis inside a package but it is difficult to reflect a momentarily changing condition of the device under test (DUT) to the simulation.

In this paper, we propose a method of real-time imaging of temperature distribution inside a DUT. This method is based on a "real-time simulation" concept as shown in Fig. 1. In the real-time simulation, condition monitoring of DUT and high-speed simulation were simultaneously performed. In the case of the internal temperature distribution of DUT, a high-speed thermal simulation is performed by using a monitored surface temperature as a boundary condition.

* Corresponding author.
E-mail address: nave@elcs.kyutech.ac.jp (A. Watanabe).

2. Basic configuration of the imaging system

The system is realized by combining real-time monitoring and real-time simulation. Infrared cameras surrounding the specimen monitor the surfaces of DUT and obtain the temperature data of each pixel. The cameras must be appointed so as to be able to measure the temperature of all surfaces of the object; therefore, our system supports up to six cameras (Optris PI-160 or PI-640). When the obtained infrared image is warped due to the position between the camera and DUT, the image is corrected by image conversion.

The obtained temperature data is processed by an original high-speed thermal simulator as a boundary condition. The simulator calculates the inside temperature distribution of DUT and consequently the thermal distribution is displayed in real time. The thermal simulator solves a discretized three-dimensional equation for non-steady state heat conduction. In the case of one-dimensional heat conduction, the procedure is as follows. The equation for non-steady state heat conduction is:

$$c\delta\frac{dT}{dt}=\frac{dF}{dx}+Q \qquad (1)$$

c: specific heat, δ: density of the materials,
T: temperature, F: heat flux, x: distance,
Q: heat generation density.

The left side and right side of the equation are discretized by the finite-difference method and finite volume method, respectively [6]. In

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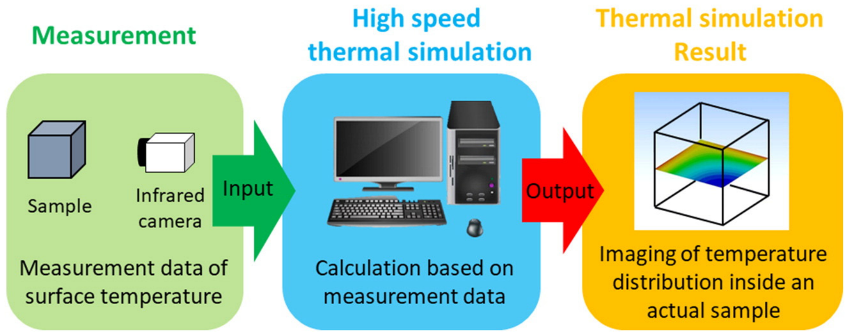

Fig. 1. Method of real-time imaging of temperature distribution inside DUT.

the finite volume method, the solution domain is divided into a finite number of contiguous control volumes (CVs), and the conservation equation is applied to each CV.

The discretized equation for n CVs is expressed as:

$$c_n \delta_n \Delta x_n S_n \frac{T_n - T_n^{old}}{\Delta t} = (F_{n-1} - F_n) + Q_n \Delta x_n S_n \quad (2)$$

Here x_n and S_n are position and area of the nth CV, respectively. $T^{old}{}_n$ is the temperature of the volume at the previous state. Heat flux F_n is converted to a function of T_n by Fourier's law for heat diffusion; therefore, Eq. (2) is described as a function of T. The temperature distribution is obtained by solving a simultaneous equation of T formed by each mesh. In this manner, the exchange of heat at the surface is not necessary to consider by using the measurement temperature as a boundary condition, because that is T of CV at the surface. We corded the simulator with MATLAB (MathWorks).

The accuracy of the developed simulator was confirmed by comparison with a commercial simulator (ANSYS Icepak). Several types of simulation model were used for the validation, *e.g.* (1) the temperature of one or some surfaces is fixed to high or low temperature and that of the others is adiabatic, (2) the temperature of all surfaces is fixed, (3) a part of the surface is adiabatic, (4) the object has a complex shape. Fig. 2 show the results of (1) and (2) for example. The relative error in the temperature of the simulation result was within 0.0006% for all models.

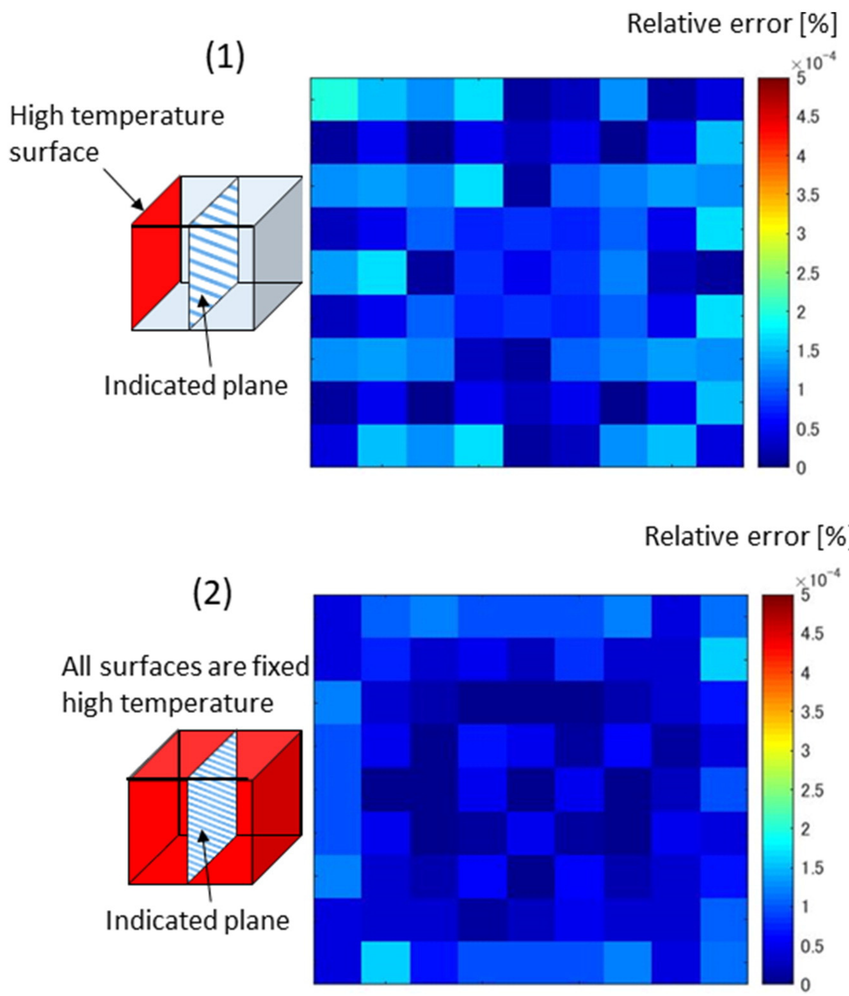

Fig. 2. Error mapping comparison between developed thermal simulator and a commercial simulator.