View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Kyutacar : Kyushu Institute of Technology Academic Repository

九州工業大学学術機関リポジトリ
Kyutacar
Kyushu Institute of Technology Academic Repository

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

著者	Watanabe A., Nagao R., Omura I.
journal or publication title	Microelectronics Reliability
volume	76-77
page range	490-494
year	2017-07-11
URL	http://hdl.handle.net/10228/00007289

doi: info:doi/10.1016/j.microrel.2017.06.092

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

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 1s and the temperature difference at the Si chip was within 2 ^{O}C by a comparison with that estimated from forward voltage drop.

Corresponding author.
nave@elcs.kyutech.ac.jp
Tel & Fax: +81 (93) 884 3298

© 2017. This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/

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

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

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.

2 lines space

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.

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.

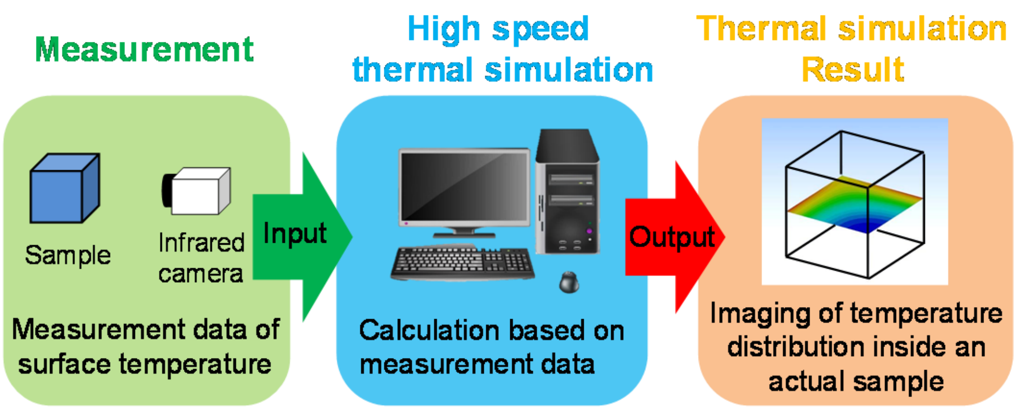

Fig. 1. Method of real-time imaging of temperature distribution inside DUT.

* Corresponding author. nave@elcs.kyutech.ac.jp
Tel&Fax: +81 (93) 884 3298

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

$$c\delta \frac{dT}{dt} = \frac{dF}{dx} + Q \tag{1}$$

c: specific heat, δ: density, 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 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

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

Here x_n and S_n are distance and area of each 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. Figure 2 show the results of (1) and (2) for example. The relative error in the temperature of the simulation result was within

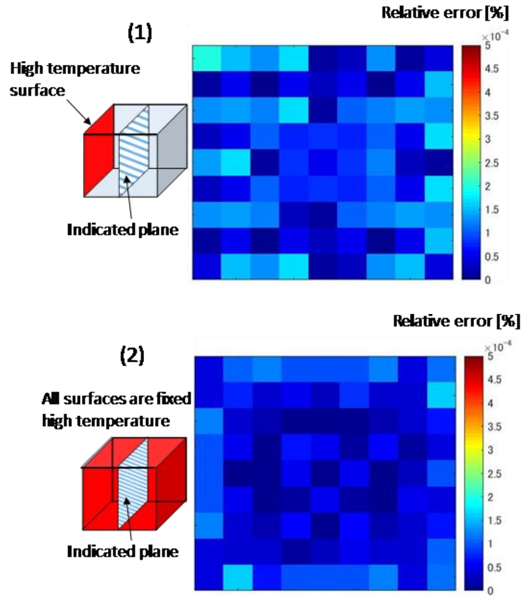

Fig. 2. Error mapping comparison between developed thermal simulator and a commercial simulator.

0.0006% for all models.

The simulation time depends on the number of CVs, namely that of meshes. Our present system supports up to 27000 meshes. Table 1 shows the simulation time with various mesh numbers.

Table 1
Simulation time with number of meshes

Number of meshes	Mesh number of x, y, z axis	Simulation time [s]
1000	10 × 10 ×10	0.0018
8000	20 × 20 ×20	0.0323
27000	30 × 30 × 30	0.2484

The accuracy of internal temperature distribution obtained by our system was also confirmed experimentally with a metal-block specimen heated by a heat gun (Fig. 3). In this case, the boundary condition to solve the equation for heat conduction was the temperatures of the specimen surface, because there was no heat generation at the CV inside the specimen. These temperatures were measured by five IR cameras to compensate for the area hidden by a post and the thermometers. The temperature at several points in the block measured by the thermometer agreed well with that obtained by our system.

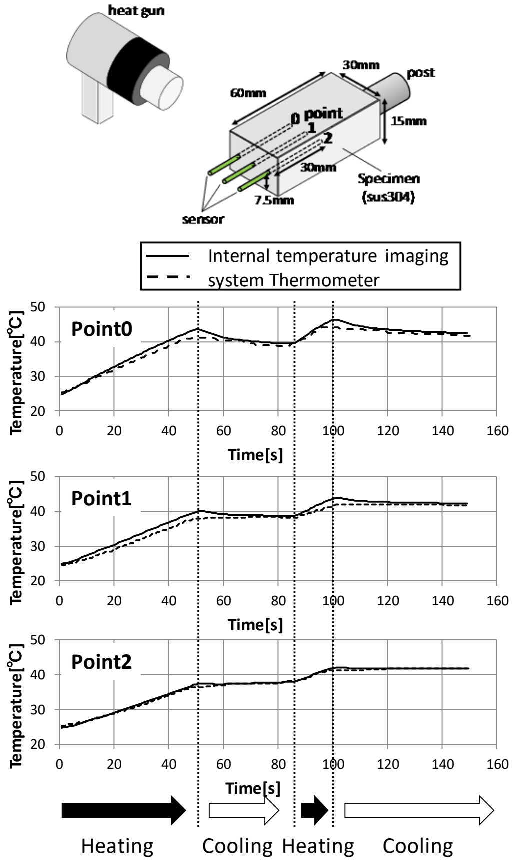

Fig. 3. Comparison between our system and thermometer. Number of meshes was 15 × 15 × 20 (4500 CVs). The specimen surface was painted by a black body spray to uniform infrared emissivity.

3. Application to power cycling test

When the system is applied for a power cycling test, it is necessary to consider the self-heating of the semiconductor chip in the package. In this application, we assume that the applied electric power is dissipated only at the chip and the temperature of the chip is uniform. The chip temperature is estimated from the applied power and the chip volume. For the simulation, the temperature of CVs that corresponds to the chip region is uniformly the estimated temperature.

A demonstration was performed with a TO-220 packaged diode (FAIRCHILD RHRP3060). The applied power cycle was 5 s heating up and 5 s cooling down. The applied current was 3 A and the applied power was approximately 5 W/s. The frame

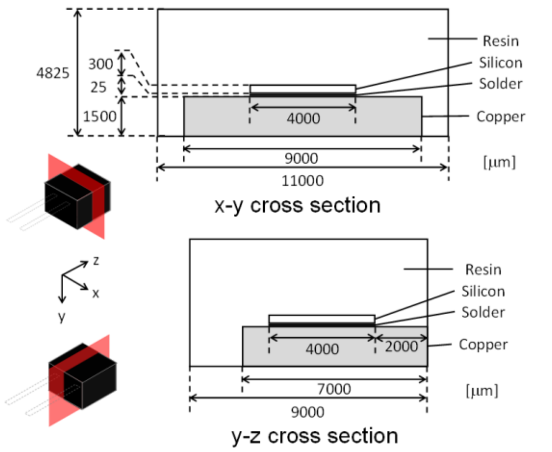

Fig. 4. Thermal simulation model.

rate was set to 1 fps. In this demonstration, five cameras were used to monitor the entire surface of the DUT. The DUT surface was painted by a black body spray to uniform infrared emissivity. The simulation model of the device was simplified with a base copper plate, a solder layer, a Si chip and a resin package as shown in Fig. 4. The total mesh number was 4356 (x = 22, y = 11, z = 18). The mesh size along the x- and z-axis was 0.5 mm. The mesh size along the y-axis was adjusted to the thickness of the constituent material. That is 0.3 mm at the Si chip, 0.025 mm at the solder layer and 0.5 mm at other materials. The applied stress current and voltage were also monitored. The temperature of the Si chip was estimated from these monitored values.

Figure 5 shows the graphical user interface (GUI) of the system. Surface temperatures monitored by infrared cameras are indicated in the upper right area. Each of the five cameras obtains temperature data of one or two surfaces of DUT. A calculated temperature distribution is indicated in the bottom area. Temperature distribution at any plane in the DUT can be indicated because of 3-dimensional thermal simulation. The GUI also indicates the power cycling condition and the junction temperature T_j of the Si chip estimated from forward voltage drop at 100mA applied in the cooling period of power cycling.

Figure 6 shows temperature distribution images in a device under the power cycling test. The results of one certain cycle and three different planes in each x-y, y-z and z-x cross section at 6 s are indicated in the figure. In the heating process, the temperature of the Si chip and the copper base plate elevated at first. Once the stress current was turned off, the

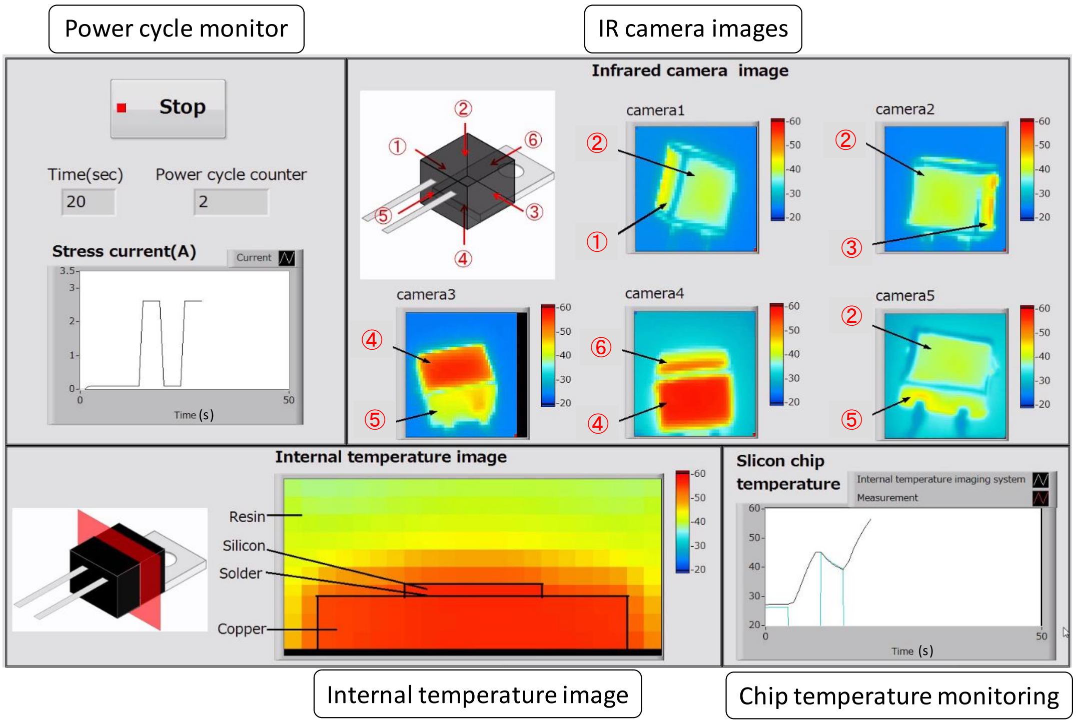

Fig. 5. Graphical interface of the system. Temperature distribution inside the package is shown in the bottom area.

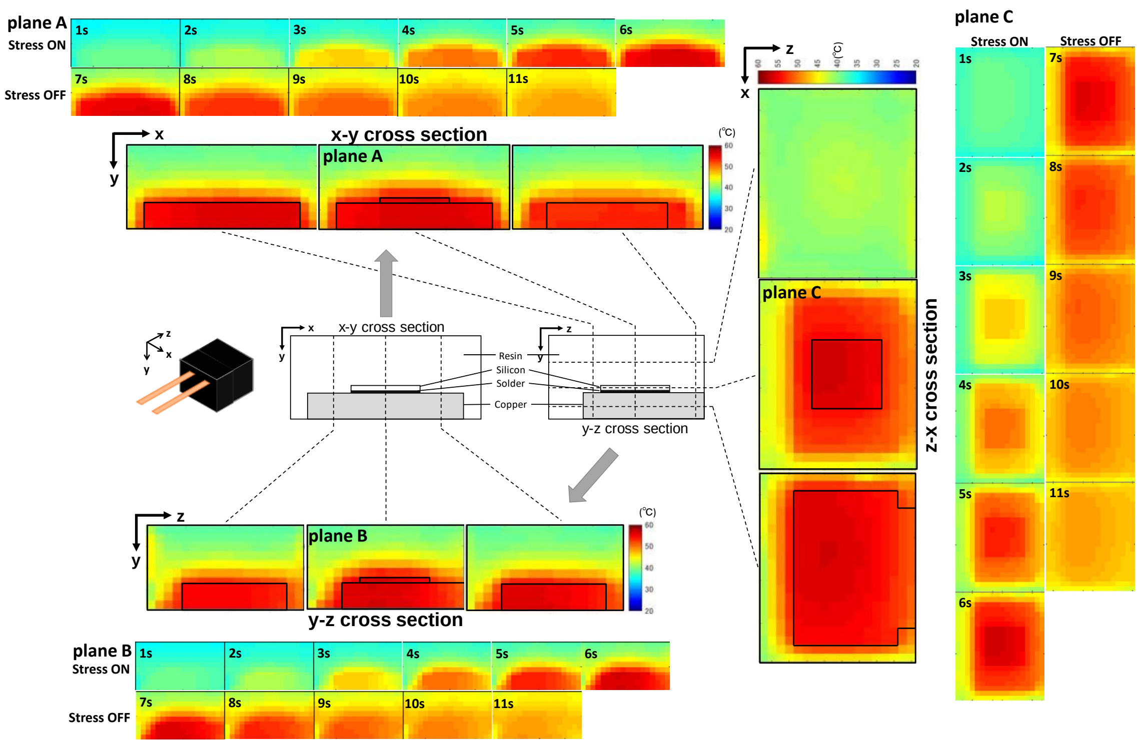

Fig. 6. Change in temperature distribution inside the package under a power cycling test.

temperature inside the package became uniform gradually and then cooled down.

Figure 7 shows the temperature profile of the Si chip in the DUT. The result of our system is

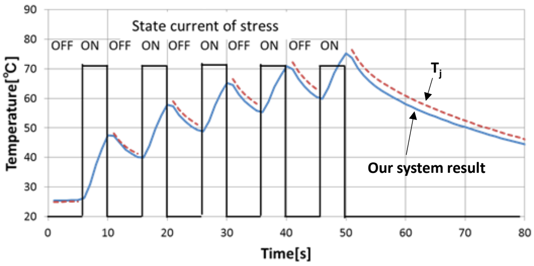

Fig. 7. Temperature profile of Si chip in DUT.

compared with junction temperature T_j estimated from forward voltage drop at low current. Although T_j could be estimated only in the cooling period, it indicated almost the same behaviour and the difference in temperature was less than 2^{O}C. Moreover, the temperature change of the chip during the heating period, which is difficult to obtain by non-destructive measurement, could also be estimated by this system.

4. Discussion

The proposed system is applicable to a system by which the exchange of heat is confined at the surfaces, for example external heating or air cooling, without simulation of the heat exchange because the measured surface temperature is directly imputed as a boundary condition of the simulation. On the other hand, in the case of power cycling, heat generation of the semiconductor chip is also considered for the temperature simulation. For the demonstration, it is estimated simply from applied power and chip volume. According to Fig. 7, our modelling of the heat generation is appropriate for the demonstration condition but it needs to be validated experimentally in more detail.

This system can be applied to the analysis of localized parts in the device or a large module, although it is necessary to improve the processing speed because the calculation time depends on the number of meshes. Moreover, the method should be adapted to a more representative case in which the base plate is mounted on a heat sink. It is difficult to solve the heat exchange at heat sink because the proposed method deals only heat conduction in a package. Therefore, with appropriate modelling of a heat sink, the proposed method can be applied.

5. Conclusion

This paper proposes a real-time imaging method to obtain temperature distribution in a power device package during operation. By combining monitoring and simulation, temperature distribution in the power device package was successfully visualized in a completely non-destructive manner.

Acknowledgements

A part of this work was supported by SCAS (Sumika Chemical Analysis Service).

References

[1] C. Herold, J. Franke, R. Bhojani, A. Schleicher, J. Lutz, Requirements in power cycling for precise lifetime estimation, Microelectron. Reliab. 58 (2016) 82-89.

[2] T. Kociniewski, J. Moussodji, Z. Khatir, Temperature mapping by l-Raman spectroscopy over cross-section area of power diode in forward biased conditions, Microelectron. Reliab. 55 (2015) 547–551.

[3] C. van der Broeck, M. Conrad, R. W. De Doncker, A thermal modeling methodology for power semiconductor modules, Microelectron. Reliab. 55 (2015) 1938–1944.

[4] U.M. Choi, F. Blaabjerg, F. Iannuzzo, S. Jørgensen, Junction temperature estimation method for a 600 V, 30A IGBT module during converter operation, Microelectron. Reliab. 55 (2015) 2022–2026.

[5] M. Riccio, L. Maresca, A. Irace, G. Breglio, Y. Iwahashi, Impact of gate drive voltage on avalanche robustness of trench IGBTs, Microelectron. Reliab. 54 (2014) 1828–1832.

[6] J.H. Ferziger, M. Perić; Computational methods for fluid dynamics (3rd edn), Springer, Berlin, 2002, p36 and pp 71-89.