Abstract

One cause of power semiconductor failures is cracks or breaks in joints caused by thermal stress due to differences in thermal expansion coefficients of components. To reproduce this failure phenomenon, temperature cycle tests and power cycle tests are performed. Since stress concentration locations and creep change according to the temperature rise time, power cycle tests require appropriate test conditions to be set. But since amounts of generated heat vary from device to device, there are no guideline indicators to rely on.

This research consisted of performing power cycle testing done with varying temperature rise times, and investigating the relationship between power semiconductor reliability test conditions and solder joint deterioration or life. To simplify parameters, we used a ceramic heater as a surrogate for a heat-radiating chip in our evaluations.

The information in this report is an expanded and reorganized version of information presented at the 28th Spring Conference of the Japan Institute of Electronics Packaging.

1. Introduction

One cause of power semiconductor failures is cracks or breaks in joints caused by thermal stress due to differences in thermal expansion coefficients of components. When a crack or break occurs in a joint, the heat transfer path is blocked, resulting in heat becoming trapped in the semiconductor power chip, causing thermal runaway. To reproduce this failure phenomenon, temperature cycle tests and power cycle tests are performed. Power cycle tests involve powering the device intermittently, and varying the temperature over a short period of time. But since in practice, amounts of generated heat vary from device to device, there are no reference values or guideline indicators to rely on. And since temperature conditions and temperature rise times may possibly affect failure modes and component life, there is a need to determine causal relationships between stress and deterioration.

The purpose of this research was to examine die-attach joints of power semiconductors to investigate the relationship between joint deterioration or life, and reliability test conditions. To set test condition guidelines appropriate for the application of this research, this paper reports the results of power cycle testing done with varying temperature conditions and temperature rise times.

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2. Specimens

Devices such as IGBT (insulated-gate bipolar transistor) modules have a multilayered internal structure composed of compound materials, making it difficult to evaluate only specific locations using failure modes inherent in individual joints or materials. To enable us to examine die-attach joints, the specimens evaluated by this research were manufactured with a simpler structure specialized for joint evaluation. Figure 1 shows photos of the external appearance of the specimens, and a simplified diagram of their structure. Instead of a heat-generating power semiconductor chip, specimens had a ceramic heater mounted on a copper heat-radiating substrate. The amount of generated heat was adjusted by varying the heater’s voltage.

![Figure 1 Specimens used for evaluation](image1)

![Figure 2 Adjusting temperature by heater voltage](image2)

Figure 2 shows an example of the changes in the power cycle temperature waveform created by the heater voltage, when the temperature was cycled between 0 and 175°C. As shown in the diagram, temperature rise time can be adjusted, and increasing the heater voltage enables a faster cycle rise time. Specimens were provided with two different patterns, formed from nickel/gold plating on the bottom surface of the ceramic.
heater for mounting to the substrate. A pattern for radiating heat to the substrate was provided over most of the center, and a pattern for measuring electric resistance was provided on the four corners for early detection of cracks formed in the joint. Specimens were manufactured in a nitrogen atmosphere to prevent oxidation. To prevent voids, nickel ball-infused sheet solder (Su-3.0 Ag-0.5 Cu) made by Senju Metal Industry was used for the joint material, and a flux with a viscosity of 10 Pa·s (also made by Senju) was used. We initially tried mounting with paste solder, but since a large number of voids resulted, we succeeded in manufacturing low-void specimens by using sheet solder.

3. Test Method

We performed power cycle testing with temperature control (constant ΔT) done by the center surface temperature of the heater top surface. We used three test conditions. Table 1 shows the power cycle test conditions. As a reference, Condition 1 was a temperature condition of 70 ↔ 150°C (ΔT = 80°C), a condition designed for testing a vehicle-mounted power module. The heater voltage was adjusted to make the initial temperature rise time about 10 seconds. We also performed testing with an extreme temperature condition of 0 ↔ 175°C (ΔT = 175°C), as an accelerated condition that is demanding for soldered joints. We investigated the effect of the temperature condition difference between this condition and Condition 1. When testing with a temperature condition of 0 ↔ 175°C (ΔT = 175°C), we used initial temperature rise times of 10 seconds (Condition 2) and 60 seconds (Condition 3), and examined the effect of the difference in rise times. The cooling method for all conditions was air-cooling, and only during cooling, we used a fan to cool specimens from the substrate bottom surface. Accordingly, testing was done in a temperature chamber (ESPEC model SH-241) stabilized at a temperature 5°C lower than the minimum temperature for each test condition. Measurement was performed using a multi-channel resistance measurement system (ESPEC model AMR-280-P) to measure four resistance measurement patterns provided on the outer circumference of the heater joint. We measured the heater top surface center temperature and substrate bottom surface center temperature.

4. Results and Discussion

Figure 3 shows the life (in cycles) of an outer circumference solder joint, evaluated from the change in resistance value in each test condition. Channels 1 and 4 for Condition 1 had resistance values that fluctuated starting directly after the start of testing, and were deemed initial failures. But the remaining channels had longer lives than all channels for Conditions 2 and 3, indicating that differences in temperature conditions
showed up as differences in life. There was no significant difference in the result when only temperature rise time was changed for Conditions 2 and 3.

![Figure 3 Relationship between change in resistance value and life](image)

We measured the temperature at two locations during the test, and found that the temperature waveform changed as the test progressed. Figure 4 shows the power cycle temperature waveform during the test, and the rate of change in temperature rise time for the top surface temperature.

![Figure 4 Temperature waveform and temperature rise time for power cycle testing](image)

For the top surface temperature subjected to temperature control during power cycle testing, we compared the initial temperature waveform (solid line) and the temperature waveform over the course of the test (broken line).
As shown in Figure 4, the temperature waveform exhibited almost no change after 30,000 cycles under Condition 1, and the temperature rise time changed by less than 10%. Under Conditions 2 and 3, the temperature waveform exhibited different shapes before and after testing, and the temperature rise time decreased in a smaller number of cycles than for Condition 1. As shown in Figure 5, we obtained similar results when measuring the temperature at the center of the substrate’s bottom surface. There could be several causes for the decreasing trend of Conditions 2 and 3, such as differences in joint deterioration or differences in temperature rise time conditions. When we extracted the specimens after testing, we found that the ceramic heater in the specimen used for Condition 2 had separated from the substrate (Figure 6). This finding indicates that the temperature waveform changes and decreasing trend of Condition 2 are the result of joint deterioration, and that the main cause of the deterioration is thermal fatigue. In future, we will verify the reproducibility of our results and study the causal relationship between deterioration and temperature waveform changes.

Figure 5 Bottom surface center temperature vs. number of test cycles

Figure 6 Photo showing external appearance of specimen after testing (Condition 2)
5. Conclusion

The results of the resistance value measurements we obtained from our tests indicated differences in life caused by the differences between the $70 \leftrightarrow 150^\circ C$ and $0 \leftrightarrow 175^\circ C$ temperature conditions. Various behaviors were also exhibited in temperature waveform changes and temperature rise time results, and in future we will verify their reproducibility and investigate their causal relationship with joint deterioration. We used the extreme $0 \leftrightarrow 175^\circ C$ ($\Delta T = 175^\circ C$) temperature condition to obtain failure results faster, but we feel a temperature condition of $175^\circ C$ was excessive since the heater in the specimen for Condition 2 separated from the substrate, and the specimen for Condition 3 exhibited deterioration soon after the start of the test.

Bibliography