Evaluation Technology for Quality and Reliability of Semiconductor Device

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Abstract

In order to supply high-quality and reliable products to our customers, our Materials & Semiconductor Device Analysis Center conducts quality evaluations of semiconductor devices to be used in our products and in reliability tests of peripheral materials. Since such evaluations and testing activities are promptly and accurately carried out, various problems caused in devices and peripherals are duly solved. As a result, quality and reliability of products are improved.

To avoid variation of electrical characteristics at the time of X-ray Computed Tomography (CT) testing, we optimized X-ray irradiation conditions. By using a cooling stage, we improve the processing accuracy of a sample cross-section in the Focused Ion Beam (FIB) processing.

In the field of reliability evaluation technology, we worked on technical development such as the durability test on device peripheral materials by using power cycle test equipment to examine thermal stresses. All in all, these activities are extremely effective in the prevention of making defective goods and an improvement of quality and reliability of our products.

1 Preface

We supply a variety of products to customers such as, electronic equipment, Information Technology (IT) equipment, and substation equipment. These products contain various kinds of devices such as power semiconductor devices; each device is required to assure high quality. In order to supply high-quality and reliable products to the customers, our Materials & Semiconductor Device Analysis Center conducts evaluation of quality and reliability of semiconductor devices to be used in these products.

For the quality evaluation of semiconductor devices, new devices under consideration of adoption are investigated to identify any internal material or structural defects. “Quality analysis” is carried out to presume probability of future malfunction. “Failure analysis” is also conducted to pursue a possible cause of failure and whether it occurred during product manufacturing or at the customer site. For these analytical approaches, X-rays may be used to examine inner structures in a non-destructive mode or inner structures may be analyzed by opening the resin package.

For the reliability evaluation of semiconductor devices, in order to predict and/or prevent the occurrence of any failure of devices or their peripheral materials, we uncover any potential defects by applying environmental or thermal stresses to the test sample. We then apply a method to estimate the product life and confirm if the device meets the required performance.

This paper introduces our analytical evaluation technology to support quality and reliability of our products by actively using our quality evaluation and reliability evaluation method.

2 X-Ray Observation Technology and Optimization of Irradiation Conditions

X-ray observation is widely used in the industry as a non-destructive analytical approach by which inner structures of semiconductor devices can be observed without opening their packages. Recently, observation by X-ray Computed Tomography (CT) became dominant and popular. CT observation, however, contributes to a long duration of X-ray irradiation and as a result, electrical characteristics of semiconductor devices may be changed after

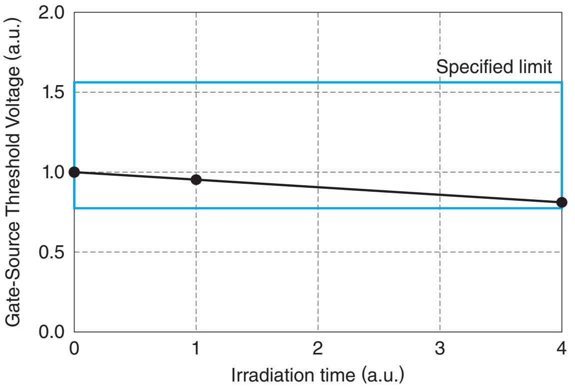

Fig. 1 Example of Gate-Source Threshold Voltage Dependence on Irradiation Time

The threshold voltage varies if the X-ray irradiation time to MOSFET is increased.

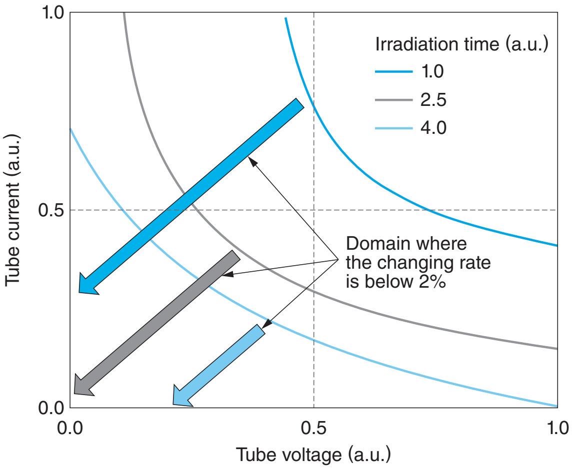

Fig. 2 Example of the Domain below 2% Voltage Changing Rate of the MOSFET Threshold Voltage Value

When irradiation time is increased, the domain of the tube voltage and the tube current are narrowed in the case that the threshold voltage changing rate is below 2%.

observation. In order to avoid misjudgment due to such characteristic changes, we optimized X-ray irradiation conditions by actively using Response Surface Methodology (RSM), a statistical method.

As a target semiconductor device, we selected a Metal Oxide Semiconductor Field-Effect Transistor (MOSFET). **Fig. 1** shows an example of gate-source threshold voltage (“threshold voltage” hereafter) dependence on irradiation time. The threshold voltage is the most significant parameter in electrical characteristics. The CT is adopted for X-ray equipment.

In the next phase, we checked the relationship between X-ray irradiation conditions and threshold voltage. Assuming that round robin experiment is carried out on three factors (tube voltage, tube current, and irradiation time) twice repeatedly at three levels, the total number of experiments is 54 times (= 3^3 × 2). For this time, based on the empirical data, the relationship between characteristics and factors (evaluation conditions of characteristics) was modeled with a low-order polynomial (generally, linear to quadratic) to lower the number of experiments to 17 times. Variation in threshold voltage was evaluated with the rate of change given by Expression (1) below.

$$\text{Rate of change} = (1 - Vth\_a / Vth\_b) \times 100\ (\%) \quad \cdots\cdots (1)$$

Vth_a: Threshold voltage after irradiation
Vth_b: Threshold voltage before irradiation

Generally, the higher the tube voltage and tube current, the clearer the X-ray image. In this case, however, it is necessary to take into consideration the tradeoff between variation in threshold voltage and definition of X-ray image. **Fig. 2** shows an example of the domain below 2% voltage changing rate of the MOSFET threshold voltage value. The domain is a downward area below each curve indicated by an arrow.

As mentioned above, we visualized variation in the MOSFET threshold voltage caused by X-ray irradiation factors and optimized the conditions of X-ray irradiation.

3 Improvement of Cross-Section Observation Technology for Semiconductor Devices

Cross-section observation is an analytical approach to inspect the inner structure of devices by making their sections. In doing so, we check the state of solder joints and galvanization in semiconductor devices mounted on the electronic substrates and check the structural analysis on IC chips.

Fig. 3 shows an electron microscope image of an IC chip cross-section processed by using Focused Ion Beam (FIB). The FIB is a processing machine that works by using ion beams. With an electron microscope equipped with the FIB, it is possible to process a cross-section while watching an enlarged image of a micro-spot of some μm in size which is impossible to see with the human eye.

Next, regarding the observation of lead solder cross-section by using FIB, we describe here the

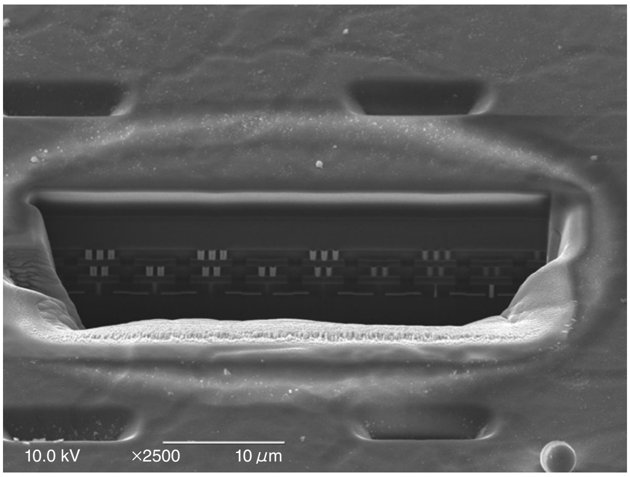

Fig. 3 **FIB Section Processing for IC Chip**

The IC chip is FIB-processed to analyze the cross-section structure of the IC chip.

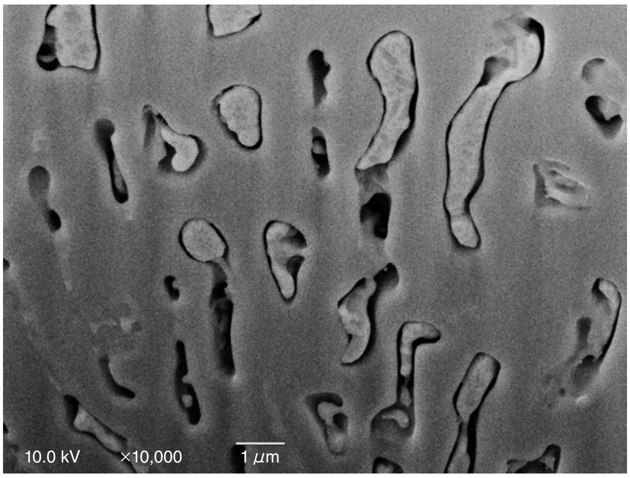

Fig. 4 **Electron Microscope Image of Lead Solder which was FIB-Processed at Room Temperature**

When lead solder is FIB-processed at room temperature, voids are created in the grain boundary of lead and tin by the effect of processing heat.

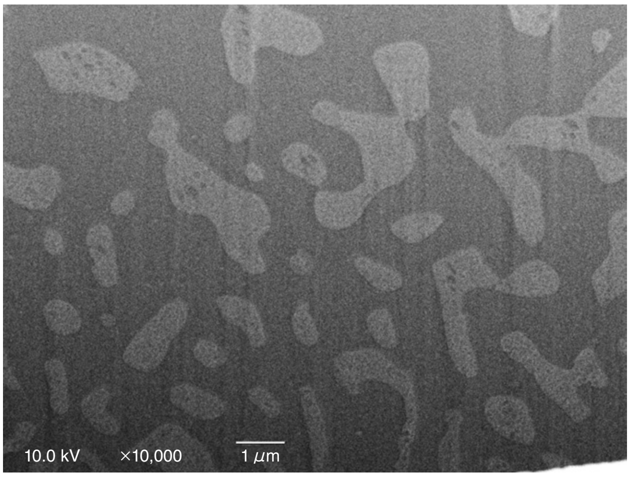

Fig. 5 **Electron Microscope Image of Lead Solder which was FIB-Processed at a Low Temperature (−50℃)**

Using a cooling stage, the specimen is chilled down to −50℃ and FIB-processed. Then, heat-borne melt damage can be relieved for metals with low melting points.

differences in thermal conditions at the time of FIB processing. **Fig. 4** shows an example of an electron microscope image of lead solder which was FIB-processed at room temperature and **Fig. 5** shows an electron microscope image of lead solder which was FIB-processed at a low temperature (−50℃). In the cross-section processed at room temperature, voids can be observed in the grain boundary of lead and tin. No voids can be seen in the section chilled at −50℃. Suggested by the result of this comparison, we recognized that a metal with a low melting point can be melted by heat generated during FIB cross-section processing done at room temperature. In addition, we confirmed that there is an effect of reducing the melting by chilling a sample.

4 Reliability Evaluation Technology Based on Thermal Characteristics of Power Semiconductor Devices

The power cycle testing equipment utilizes the power semiconductor device itself as a heat source so that thermal characteristics of the heat dissipation path from the chip to the atmosphere can be measured during the cooling temperature changes. **Fig. 6** shows an example of the general cumulative structure function. The structure function expressing a relationship between thermal resistance and thermal capacitance can be obtained through measurements. When this structure function is analyzed, it becomes possible to evaluate thermal characteristics.

Regarding the lifetime of a power semiconductor device, heat is an essential factor. Some practical examples of reliability evaluation are shown below.

Fig. 7 shows an example of thermal resistance evaluation of power converter equipped with power semiconductor devices. We made an evaluation to check if the chip junction temperature attains the design value when any arbitrary power input is applied to the module chip by assuming the actual operation. The module chip is of the Insulated Gate Bipolar Transistor (IGBT) equipped with cooling fin unit.

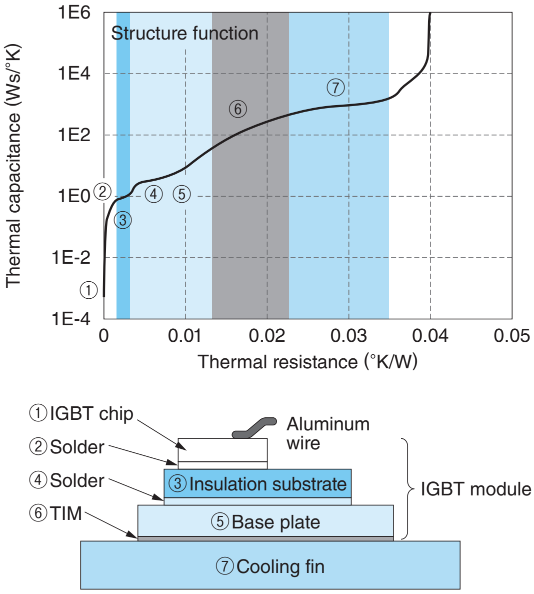

Fig. 6 Example of General Cumulative Structure Function

Thermal characteristics obtained from transient thermal impedance measurement are shown. Thermal resistance is arranged on the axis of abscissas and thermal capacitance is on the axis of ordinates. Thermal characteristics of heat dissipation path from the chip (junction) to ambient are shown.

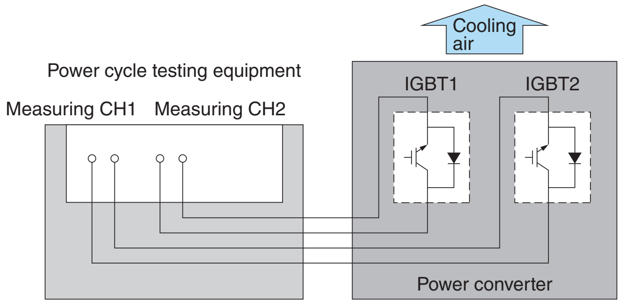

Fig. 7 Example of Thermal Resistance Evaluation of Power Converter Equipped with Power Semiconductor Devices

For a power semiconductor device with two IGBTs, a load power modeling actual operation is fed from the power cycle testing equipment. The device is under the forced air-cooled condition by means of a cooling fin unit. This is to evaluate the chip junction temperature and calculate thermal resistance values between the chip junction and ambient.

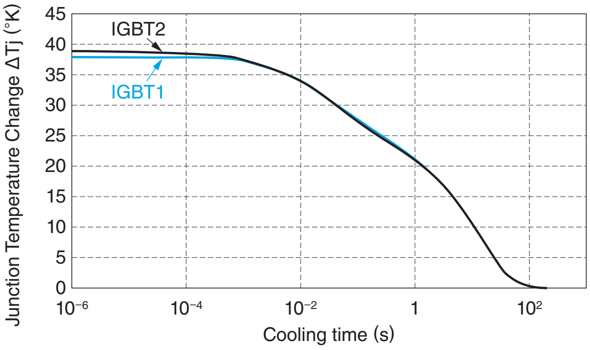

Fig. 8 Result of Measurement of Chip Junction Temperature Change ΔTj during Load Power Off (Cooling) Period

The behavior of chip junction temperature reduction during load power OFF (cooling) period is shown. Junction temperature change attributable to load power amounts to a maximum of approximately 38 to 39°K. After that, the temperature is sufficiently cooled down during power OFF period.

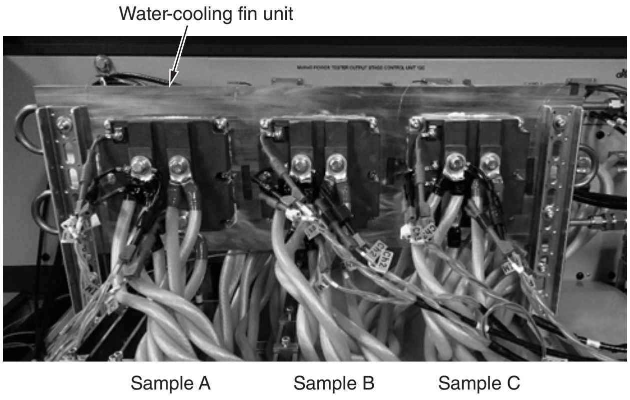

Fig. 9 Test Samples

Three IGBTs of the same type are used for evaluation. Three different types of TIM are applied on each IGBTs. They are vertically mounted on the water-cooling fin unit.

As shown in **Fig. 8**, the chip junction temperature change ΔTj was found to be approximately 38 to 39°K. This figure is close to the calculation value of about 40°K and therefore, the validity of the design was confirmed.

For the reliability of entire power semiconductor devices, reliability of peripheral materials like heat dissipation materials is also an important factor in addition to the reliability of device itself. In order to select a more highly reliable Thermal Interface Material (TIM), we made a power cycle test on three types of samples (A, B, and C) and compared and evaluated the changes over time in TIM thermal resistance.

Fig. 9 shows test samples. The TIM is applied to an IGBT module and this module is mounted on a water-cooling fin unit. Since the water-cooling fin unit is mounted vertically, conditions for simulation are rigorous for the TIMs. A power cycle test was carried out on IGBT modules under the current carrying condition that the case temperature change ΔTc = 80°K and the chip junction temperature change ΔTj = 100°K. **Fig. 10** shows an evaluation result of TIM on thermal resistance change over time. A trace of dripping of TIM was seen in Sample A

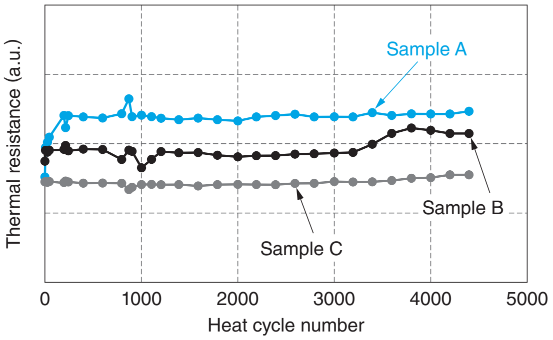

Fig. 10 **Evaluation Result of TIM on Thermal Resistance Change over Time**

By power cycle testing, thermal resistance changes in three types of TIM are shown. For Sample A, an increase in thermal resistance is large. For Samples B and C, however, an increase in thermal resistance is small and this means that these are better than Sample A in terms of durability.

and a remarkable increase in thermal resistance was observed. In the case of Sample B and Sample C, however, an increase in thermal resistance was small. It was concluded that Samples B and C are better than Sample A in terms of reliability.

5 Postscript

This paper introduced some examples of analytical evaluation technology for quality evaluation and long-term reliability test for semiconductor devices used in our products.

Going forward, we, at Materials & Semiconductor Device Analysis Center, will work on improving analysis technology by utilizing physical analysis of electrical characteristics and non-destructive cross-section analysis. In doing so, we will ensure the quality of the semiconductor devices to be used in our products and provide reliability evaluation.