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Watanabe A., Omura I.

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Real Time Failure Imaging System under Power Stress for Power Semiconductors using Scanning Acoustic Tomography (SAT)

A. Watanabe*, I. Omura

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

Abstract

Failure mechanism of power semiconductors is captured as a movie image under power stress to the device in non-destructive way. The new technique is realized by combining a high speed Scanning Acoustic Tomography (SAT/SAM) and electrical power supply circuit for applying the power stress to the device. Water as acoustic wave couplant in SAT system, which has been a major disadvantage of the system, is utilized as coolant for stressed power to the device. Major barriers to accomplish this system are a severe noise due to a local convection with the heat and a formation of tiny bubbles on the observation surface. These problems are solved by introducing water jet along the scanning interface. This technique enables “real-time” failure analysis.

1. Introduction

A “real-time” basis analysis of a failure mechanism of power semiconductors under the power stress has significant advantages over a conventional “post defect” failure analysis (PD-FA) in capturing the real trigger point of the failure before the defects are propagated to substantially large areas. The real-time basis failure inspection requires 1) High speed imaging tool for capturing damage such as voids, cracks or detachments,
without decapsulation of devices 2) Electric power stress circuit and 3) Cooling system for DUT. Temperature monitoring system is also required for stress control.

Scanning Acoustic Tomography (SAT/SAM) [1-15] can satisfy the requirements by utilizing couplant water as coolant for stressed DUT. The demonstrated real-time basis imaging system with SAT in this paper, the couplant water tank is connected to a chiller for DUT cooling, which is an essential part in the real-time basis imaging under applying electrical power stress to the DUT. SAT system has achieved to fine resolution of less than few µm, and maximum scan speed up to 1000 mm/s [16] and the resolution and speed will be potentially improved.

In this paper, the new technique for the real-time imaging of the device failure was demonstrated using a high speed SAT. Major barrier is severe noise due to local convections of water and formation of tiny bubbles on the surface with the heat generated inside DUT. The authors solved the problem by introducing high speed water flow along the scanning interface. The movie image of inside of a TO-3P package was successfully captured with frame rate of 6 frames/min. in the scanning area of 12 × 12 mm² with 100 µm resolution under mean power stress of 134 W applied to a DUT.

2. Real-Time Failure Imaging System Set-Up

The new “real-time” imaging technique was realized by combining a high speed SAT, an electrical power supply circuit for applying the power stress to the device, and some other functions shown in Fig. 1 and table 1. This concept is as follows; A DUT is set to a waterproof holder and immersed into a water tank of a SAT stage with a cooling system. A load current is applied to the DUT as a power stress by a power supply. SAT images during the power stress test are captured as a movie. The couplant water for SAT is used as coolant for DUT and the heat generated by the power stress is diffused into the water, which enable the “real-time” basis inspection.

Figure 2 shows the photographs of the experimental set-up in the SAT stage and DUT preparation. Commercially available SAT system (FineSAT FS100III, Hitachi E&S Co., Ltd.) and a TO-3P packaged n-channel MOSFET were used for defect imaging and DUT for this demonstration. The DUT was wired for electric power stress and capsuled in a waterproof holder with epoxy resin. The observational plane (back side copper) of the device was polished to a mirror finish using slurry to obtain better resolution of SAT images. This device was fixed on the bottom of the water tank in which a radiator (aluminium pipe connected to a chiller) is placed to utilize the water as coolant. A back side copper frame of the DUT, it is common to the drain terminal of MOSFET, was set to ground voltage with power circuit design to prevent the transducer from electric damage. The temperature of the heat sink of the DUT and couplant water were monitored by fiber optic temperature probes. While the actual chip temperature was not monitored directly, the DUT temperature was able to be controlled by the couplant water temperature.

Table 1
Components of Real-Time Failure Imaging System under Power Stress Test

<table>
<thead>
<tr>
<th>Function</th>
<th>Apparatus</th>
<th>Product Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect Imaging</td>
<td>Scanning Acoustic Tomography</td>
<td>FineSAT FS100III (Hitachi E&amp;S)</td>
</tr>
<tr>
<td></td>
<td>System</td>
<td></td>
</tr>
<tr>
<td>Electrical Power Stress</td>
<td>DC Power supply</td>
<td>PS 20-54 (Nikke Techno System)</td>
</tr>
<tr>
<td></td>
<td>Stress control</td>
<td>LabView (National Instruments)</td>
</tr>
<tr>
<td>DUT Cooling</td>
<td>Water chiller</td>
<td>C-331 (Sibata Scientific Technology)</td>
</tr>
<tr>
<td></td>
<td>Radiator</td>
<td>Handmade</td>
</tr>
<tr>
<td>Water Jet</td>
<td>Water pump</td>
<td>LMB15107315 (Laing Thermotech)</td>
</tr>
<tr>
<td></td>
<td>Nozzle</td>
<td>Handmade</td>
</tr>
<tr>
<td>Temperature Monitoring</td>
<td>Fiber optic temperature sensor</td>
<td>FOT-L-SD (FISO Technologies)</td>
</tr>
<tr>
<td></td>
<td>Controller</td>
<td>UMI8 (FISO Technologies)</td>
</tr>
</tbody>
</table>

Fig. 2. DUT preparation and its setup in the SAT stage
The system is controlled via GUI on a PC display. The GUI consists of SAT controller window and power stress controller window (Fig. 3). SAT acquisition parameters such as gate of reflected echo from DUT are set in the SAT controller window and continuous scan image is displayed in the same window. The power stress parameters such as a load current, a power cycle time and a duration of the cycle, are set in the power stress controller window. Temperatures of the water and DUT surface, electric current and voltage are also monitored in this window. The power stress controller window is programmed with LabView (National Instruments).

3. SAT Image Noise with Heated Couplant

Two major problems of SAT observation under power stress were found in this experiment (Fig. 4 and 5(a)). One is a severe noise appeared as dark stripes in the image when the power stress applying. This noise is caused by a local convection just beneath the detector. The other one is a formation of tiny bubbles from heated water near the surface. Once the bubbles formed on the surface, it prevents the transmission of the ultrasonic wave into the DUT.

We solved these problems by introducing water jet system (Fig. 5(b) and the photograph was already shown in the right side of Fig. 2). This system generates a water flow of approximately 12 m/s along the scanning interface. This velocity is enough to push out the bubbles on the surface. Water pump must be started 10 minutes before to the measurement to sweep minute bubbles out of the water jet system. A clear SAT image was successfully observed under the power stress of 32 W using this water jet system (Fig. 6).

Fig. 4. Dark stripes due to a local convection (pointed by black arrows) and dark spots of tiny bubbles (pointed by gray arrows) are strongly degraded SAT image.

Fig. 5. Problems of SAT imaging under power stress (a) and their solution with high speed water jet system (b).

Fig. 6. When the water jet was started, the temperature of the heat sink immediately dropped to as same as the water temperature and the image noise of SAT were vanished.

Figure 6 also shows a cooling effect of the water jet when a continuous load current was applied to the DUT. When the power stress was turn-on, a temperature of the heat sink was jumped up immediately, then the SAT observation was started, it slightly dropped and oscillated periodically. This oscillation caused by a stirring the water by the SAT probe because that
oscillation was almost linked a scan period of SAT. Under these conditions, a temperature of the water was elevated gradually and observed images were very noisy. Once the water jet was started, the temperature of the heat sink immediately cooled down to the water temperature and the image noise were varnished. These results pointed out that the water jet along scanning interface does not affect the transmission of the ultrasonic wave, because the velocity of the wave in water (1480 m/s) is much greater than that of water jet (12 m/s), and it is important to diffuse the local convection just beneath the detector to obtain stable SAT image of DUT.

4. Case study of failure imaging of DUT

A movie capturing under power cycling test requires a high speed scan of SAT images and high resolution snapshots also need to find a slight deformation occurred inside of a DUT. The proposal protocol for

![Proposal protocol for real time failure imaging under power stress test and a result of the case study. The monitored power cycle and the series of images were obtained just before the DUT was broken. Snapshots taken at each power cycle interval were numbered with underline. Screen shots of the movie were captured when the power stress ON (numbered within round brackets) and OFF (numbered within square brackets).]
this demonstration consists of two types of imaging methods to satisfy these requests. SAT images continuously observed under a power cycle test are captured as a movie with lower resolution and snapshots are also taken in each interval of the test (Fig. 7) with higher resolution. A slight deformation take place inside of a DUT can be found in the snapshot and then the real trigger point of it also can be traced in the movie by using this proposal protocol.

The proposed technique was applied to an actual real-time failure analysis. A load current of 24 A was applied to the DUT with pulse width of 30 s and the power cycle time of 80 s. The mean power stress for the DUT was approximately 134 W. The movie images (100 µm resolution) were captured with 6 frames/min. and the snapshots (50 µm resolution) were captured after each 20 power cycle. The temperature of heat sink and couplant water was kept under 20 ºC during the observation with the water jet and the cooling system.

Scan parameters for SAT imaging of this case study are listed in Table 2. The scan area and scan pitch can be set directly via the SAT controller window in Fig. 3 and the maximum speed is automatically optimized by SAT system from these parameters. The scan speed of transducer is not constant in the maximum speed because the transducer repeats stop and acceleration during the observation. Therefore, the listed value of frame rate is an actual time required to obtain one image.

Die detachment propagation from the upper left side was successfully captured in Fig. 7 (pointed by white arrow). Furthermore, a remarkable image change is observed at the center of the die (in 13-16 frames) corresponding to the position of the bonding wire, and then the device was eventually destroyed (in 17-19 frames). Figure 8 shows the consecutive images captured from the movie in the 5th period of power cycle in Fig. 7. It is able to be traced from the movie that a damage at the right side of the die gradually propagated (between the image “i” to “m” in Fig. 8) and the other damage at the center (image (14)) suddenly appeared when the load current was turned on at 156 min. 20 s. Further scan speed improvement for higher movie image frame rate is required to analyze such abrupt failure propagation. In this case, a failure of DUT seemed to be caused by a die detachment and two successive damages at the wire bonding which occurred gradually and rapidly. This result is obtained thanks to the real-time basis failure analysis (RT-FA) technique, because it enables to distinguish some causes of a failure in time series, which is hardly by conventional PD-FA techniques.

An image noise appeared again during load current was applied to the DUT as recognized in the movie images numbered within round brackets. Moreover, a formation of tiny grains took place on the heat sink surface and it increased the roughness of the surface in the case of a higher power stress was applied. The deformation could be caused by oxidation of the surface or impurity in the water. Same phenomenon also observed, even if a lower power stress, when the temperature of the water was exceeded 60 ºC. These results implied that more improvement of the water jet system, water cooling or DUT surface treatment is necessary to apply this technique to a high power stress

### Table 2
Parameters of SAT imaging

<table>
<thead>
<tr>
<th></th>
<th>Movie</th>
<th>Snapshot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan area</td>
<td>12 mm x 12 mm</td>
<td>12 mm x 12 mm</td>
</tr>
<tr>
<td>Scan pitch (Resolution)</td>
<td>100 µm x 100 µm</td>
<td>50 µm x 50 µm</td>
</tr>
<tr>
<td>Pixel points</td>
<td>120 x 120</td>
<td>240 x 240</td>
</tr>
<tr>
<td>Maximum scan speed</td>
<td>1000 mm / s</td>
<td>600 mm / s</td>
</tr>
<tr>
<td>Actual frame rate</td>
<td>6 frames / min. (10 sec. / frame)</td>
<td>1.5 frames / min. (40 sec. / frame)</td>
</tr>
</tbody>
</table>
conditions.

5. Conclusion

A “real-time” imaging of the power device under power stress has been demonstrated. The system was realized by combining a high speed SAT, an electrical power supply circuit for applying the power stress to the device, and some other functions. A high speed water jet system and a cooling system of the couplant water solved major problems of SAT for DUT. The failure propagation occurred inside of a TO-3P package MOSFET was successfully observed by a proposed protocol in our demonstrative case.

Real-time failure analysis (RT-FA) techniques enable to image what occurs inside of DUT and it gives us helpful information about a real trigger of failure, thus it should play important role in achieving higher reliability in next generation high power density devices.

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