THE POWER TESTER 1500A— ACCELERATED TESTING AND FAILURE DIAGNOSIS OF HIGH-POWER SEMICONDUCTORS

WHITEPAPER

Mentor Graphics®

MECHANICAL ANALYSIS

INTRODUCTION

The energy demands of both consumer and industrial electronic systems are increasing, and electronics power component suppliers as well as OEMs are faced with the challenge of providing the highly reliable systems needed for aviation, electric vehicles, trains, power generation, and reusable energy production. The unique MicReD Power Tester 1500A from Mentor Graphics was designed and built to help address this challenge by accelerating testing and diagnosis of possible failure causes of power components. Two examples using IGBT modules illustrate how this issue can be addressed.

THE CHALLENGE OF RELIABILITY UNDER HIGH LOADS AND LONG LIFETIMES

Power electronics components such as MOSFETs, diodes, transistors, and IGBTs are used wherever electrical energy is generated, converted, and controlled. As the energy demands in both consumer and industrial applications are on the rise, the challenge for manufacturers of power modules is to increase the maximum power level and current load capability, while maintaining high quality and reliability. For example, railway-traction applications are expected to have a reliable 30-year lifetime, and 50,000 to millions of cycles are required by power modules incorporated into hybrid and electrical vehicles as well as solar and wind turbine energy production systems.

With this increasing pressure, innovation has resulted in new technologies such as ceramic substrates that have an improved heat transfer coefficient, ribbon bonding to replace thick bond wires, and solderless die-attach technologies to enhance the cycling capability of the modules. The new substrates help to decrease temperatures, the ribbons can take more current, and the solderless die-attach can be sintered silver which has extra low thermal resistance. In a nutshell, the thermal path has been improved. However, thermal and thermal-mechanical stress on these systems can still cause failures related to power cycling and heat. These stresses can lead to problems such as bond wire degradation (Figure 1), solder fatigue, delamination of stack-ups, and die or substrate cracks.

Figure 1: Damaged IGBT modules.

The process traditionally used for power-cycle failure testing is repetitive and time-consuming, it can only be done “post-mortem,” and it has to be done in the lab to analyze the internal condition of the package.

HOW THE POWER TESTER ACCELERATES TESTING AND DIAGNOSIS

The Mentor Graphics MicReD Power Tester 1500A is the only machine built for manufacturing as well as laboratory environments that does automated power cycling while producing analytical data for real-time failure-in-progress diagnosis (Figure 2). It’s designed to accelerate lifetime testing and improve the reliability of applications that use power electronic modules.

Figure 2: The Power Tester 1500A is built for use in semiconductor manufacturing environments.

The Power Tester 1500A is the industrial implementation of the MicReD T3Ster thermal measurement and characterization technology for electronic parts, LEDs, and systems. The Power Tester 1500A is unique in that it provides fully automated power testing and cycling at the same time, on the same machine, without having to remove the device under test during the process. A simple touch-screen interface allows a technician to use it on the manufacturing floor and/or failure analysis engineer to use it in the lab (Figure 3).

Best for analyzing MOSFET, IGBT, and generic two-pole devices, the Power Tester 1500A senses current, voltage, and die temperature while it uses structure function analysis to record changes or failures in the package structure. The machine can be used to enhance and speed up package development, reliability testing, and batch checking of incoming parts before production.

While running power cycles, the real-time structure function analysis shows the failure in progress, the number of cycles, and the cause of the failure, eliminating the need for a lab post-mortem. Conducting lengthy cycling measurements on multiple samples to estimate the cycle count range corresponding to degradation is no longer necessary. Also there's no need for an excess number of thermal measurements in this range to ensure degradation is captured. The device under test only has to be mounted and connected once; cycling and configuration is configured once.

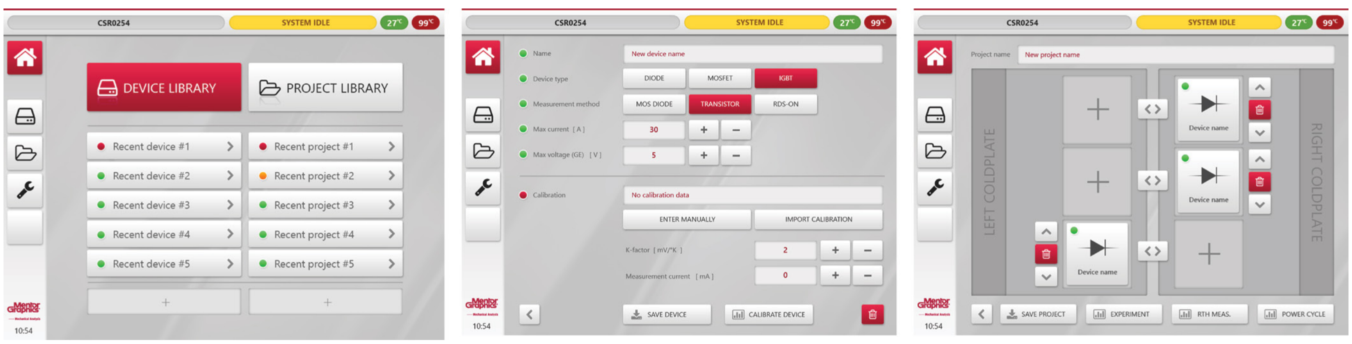

Figure 3: The Power Tester 1500A *touch-screen interface (left to right): main screen, device creation, and placing devices on the cold plate.*

"Across all semiconductor devices, the ability to pinpoint and quantify degradation in the thermal stack during development will greatly assist in the development of cost-optimized packaging solutions that are currently hampered by package reliability concerns. Mentor's Power Tester 1500A should be an invaluable tool for investigating thermal path degradation in all types of power modules."

MARK JOHNSON, PROFESSOR OF ADVANCED POWER CONVERSION, UNIVERSITY OF NOTTINGHAM

With the Power Tester 1500A, power electronics suppliers will be able to design a more reliable power electronics package and supply reliability specifications to their customers. Component designers and manufacturers can validate the suppliers' reliability specifications and characterize the package reliability. Those who are designing and manufacturing products with high requirements for reliability over the long-term will be able to test at the system level.

The Power Tester 1500A is designed to follow the JEDEC Standard JESD 51-1 static test method. Based on the captured transient response, the system can automatically generate structure functions. Structure functions provide an equivalent model of the heat conduction path expressed by thermal resistances and thermal capacitances, and they can be used to detect structural failures or to capture partial thermal resistances in the heat conduction path. The Power Tester 1500A also supports the JEDEC Standard JESD 51-14 transient dual interface measurements to determine R_{thJC}. The process of combined power cycling and R_{th} measurement mode creates stress on the device using power cycles, does regular measurement of R_{th} during the cycling, monitors system parameters such as voltage and current, and automatically increases R_{th} measurement frequency.

The testing and characterization data produced by the Power Tester 1500A can be used to calibrate and validate detailed models in FloTHERM and FloEFD thermal simulation software.

EXAMPLES OF TESTING IGBT MODULES THROUGH A LIFETIME OF CYCLES

Designers of electronics power modules and their related assemblies and systems have to ensure the thermal resistance between the chip and the base plate stays as low as possible, create reliable bonding, and ensure the die-attach layer can withstand significant thermal load during the lifecycle of the product (Figure 4). The relationship between the number of possible load cycles and the temperature/load conditions of the device has to be known to be able to make a good estimate for the power module's lifetime.

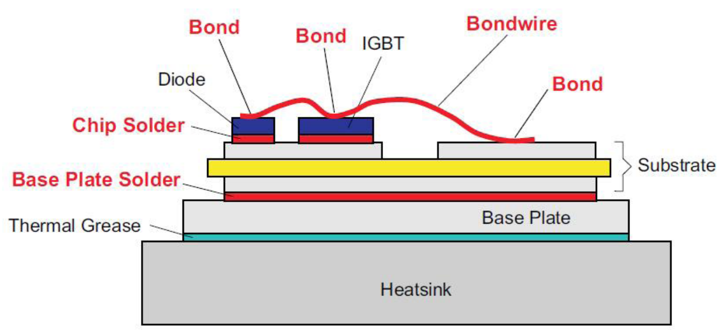

Figure 4: Cross-section of an IGBT module.

With the introduction of electric and hybrid electric vehicles, IGBT devices have gained a leading position in traction and high-voltage converter applications. Dissipated heat in the junction has a major effect on the reliability of these components. High junction temperatures and high temperature gradients during operation induce mechanical stress, especially at contacting surfaces of materials with different coefficient of thermal expansion, which can cause degradation or complete failure.

We conducted tests with four medium-power IGBT modules containing two half bridges to demonstrate the rich data that can be obtained from automated power cycling of the components. The details of these experiments were presented at the 2013 IEEE Electronics Packaging Technology Conference and the 2014 SEMI-THERM Conference [1, 2].

The modules were fixed to the liquid-cooled cold plate integrated into the Power Tester 1500A with a high-conductivity thermal pad to minimize the interfacial thermal resistance. The cold-plate temperature was maintained at 25 °C throughout the whole experiment using a refrigerated circulator controlled by the Power Tester 1500A.

The gates of the devices were connected to their drains (the so-called magnified diode setup), with each half bridge powered by a separate driver circuit. Two current sources were connected to each half bridge. A high-current source that can be switched on and off very fast was used to apply stepwise power changes to the devices. A low current source provided continuous biasing of the IGBT, which allowed device temperature to be measured when the heating current was turned off.

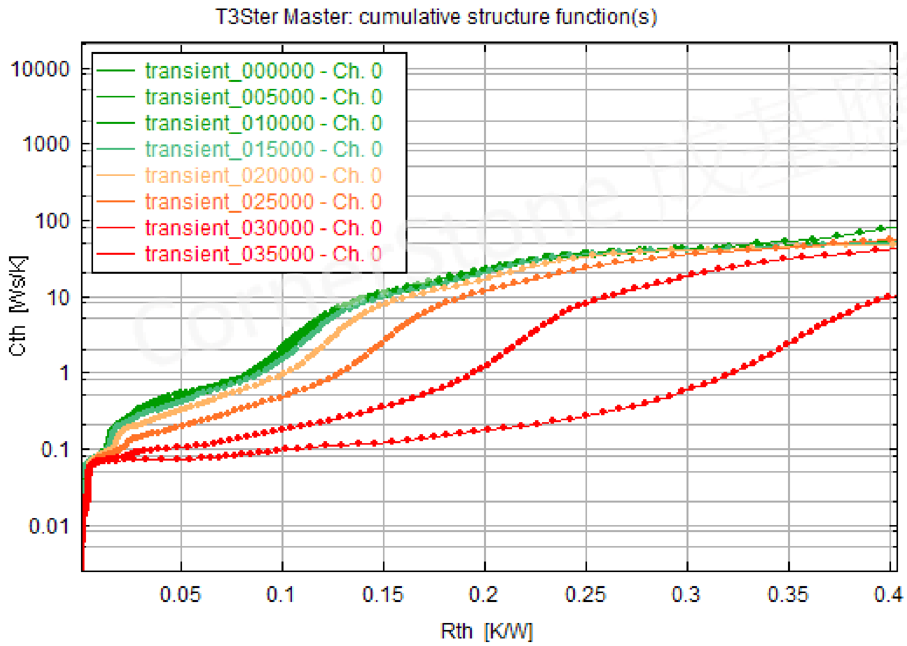

Figure 5: Structure functions of sample 0 corresponding to control measurements at various time points.

An initial set of tests on four samples was conducted using constant heating and cooling times. Heating and cooling times were selected to give an initial temperature swing of 100 °C, at ~200 W with 3 seconds heating and 10 seconds cooling. This most closely mimics the application environment, where degradation of the thermal structure results in higher junction temperature leading to accelerated aging.

Of the four devices, sample 3 failed significantly earlier than the others shortly after 10,000 cycles. Samples 0, 1, and 2 lasted longer, failing after 40,660, 41,476 and 43,489 power cycles, respectively. Figure 5 shows the structure functions generated from the thermal transients measured on sample 0 after every 5,000th cycle. The flat region at 0.08 Ws/K corresponds to the die-attach. The structure is stable until 15,000 cycles, but after that point, the degradation of the die-attach is obvious as its resistance increases continuously until the device fails. Again, the immediate cause of the device failure is unknown, but we found that a short circuit formed between the gate and the emitter, and burned spots could be seen on the chip surface.

A second set of tests were performed on an identical set of samples using the different powering strategies supported by the Power Tester 1500A. The two half-bridges in the module were mounted on the same baseplate but at separated substrates. Three devices were tested in two packages. Two of the tested devices, IGBT1 and IGBT3, were part of the same module but different half-bridge.

We kept the current constant for IGBT1, the heating power constant for IGBT2, and the junction temperature change constant for IGBT3. The settings were chosen to give the same initial junction temperature rise for all components, with 3 seconds of heating and 17 seconds of cooling, and ~240 W initial heating per device, which would ensure a fair comparison.

The entire heating and cooling transient was measured for each device in all cycles, with the following electrical and thermal parameters monitored continuously by the Power Tester 1500A:

- Device voltage with heating current turned on
- Heating current applied in the last cycle
- Power step
- Device voltage after heating current turned off
- Device voltage before heating current turned on
- Highest junction temperature during the last power cycle
- Lowest junction temperature during the last power cycle
- Temperature swing in the last cycle
- Temperature change normalized by the heating power

The full-length thermal transient from powered-on steady state to powered-off steady state also was measured after 250 cycles using a 10-A heating current to create structure functions that would investigate any degradation in the thermal stack. Again, the experiment was continued until the failure of all IGBTs.

As expected, IGBT1 failed first because there is no regulation of the supplied power as the part degrades. Interestingly, it showed no degradation in the thermal structure (Figure 6).

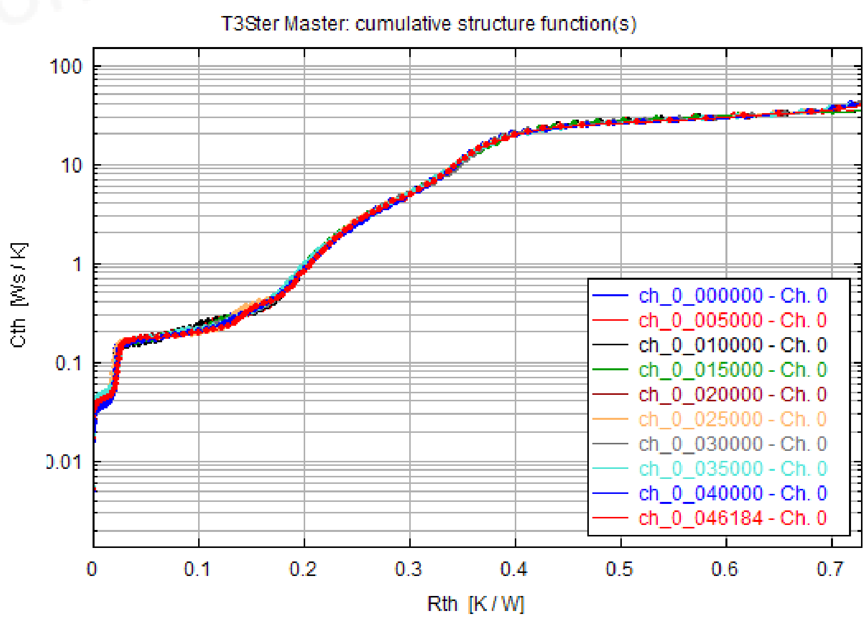

Figure 6: Change of the structure function of IGBT1 during the power cycling.

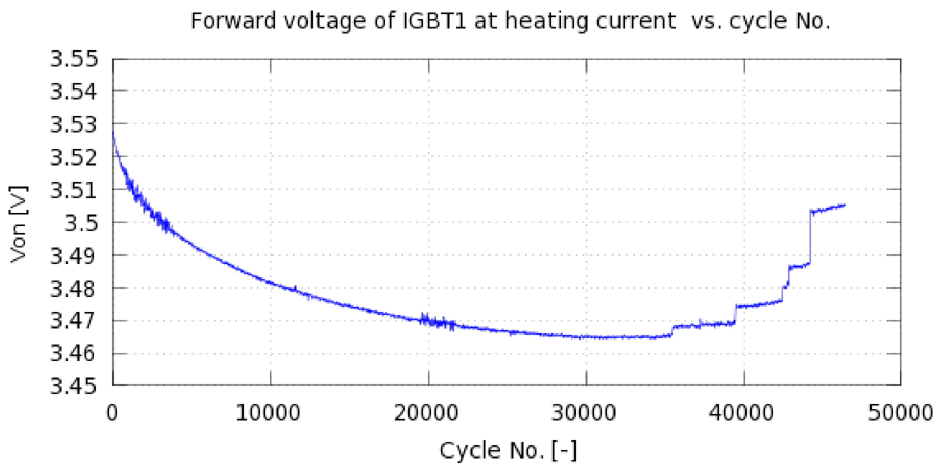

Figure 7: Forward voltage of IGBT1 at heating current level as a function of applied power cycles.

We examined the evolution of device voltage during the experiment. Figure 7 shows the forward voltage of IGBT1 at heating current level as a function of elapsed power cycles. In the first 3,000 cycles, a decreasing tendency can be seen. This initial change was caused by the slow change of the average device temperature that decreased by almost 5 °C. Despite the negative temperature dependence of the device voltage at low currents, the temperature dependence of the forward voltage became positive at high current levels.

After about 35,000 cycles this tendency changed, and the voltage started to increase slowly. This was followed by stepwise changes in the device voltage while the increasing tendency continuously accelerated until the failure of the device. The increasing voltage can be attributed to the degradation of the bond wires because the structure did not change. This also gives an interpretation to the stepwise changes of the voltage when a bond wire finally detaches. The increasing heights of these steps are caused by the increasing change in the parallel resistance sum of the bond wire thermal resistance as the number of bond wires decreases. If we use a constant current strategy, the crack of a bond wire increases the current density in the remaining bonds and accelerates the aging.

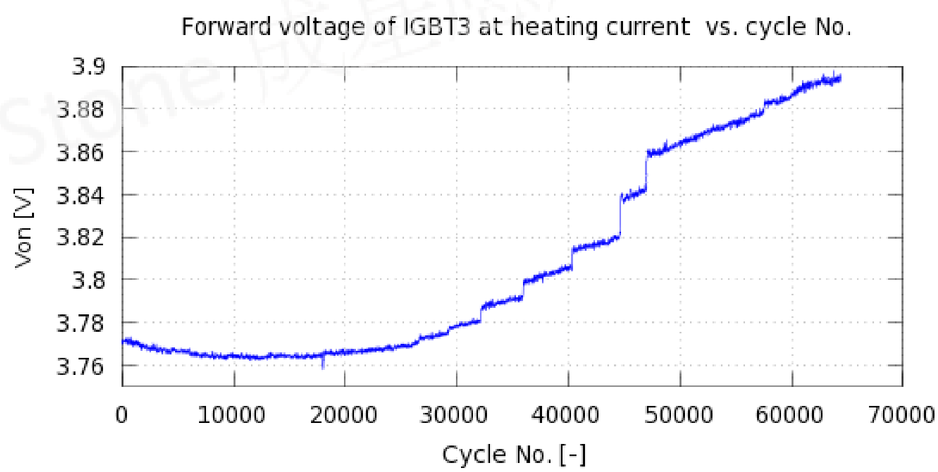

Figure 8: Forward voltage of IGBT3 at heating current level as function of applied power cycles.

Figure 8 shows the same type of curve corresponding to IGBT3. The increasing tendency of the device voltage starts even earlier, but because of the regulation to keep the junction temperature constant, the heating current was proportionally decreased. The decrease in current reduced the load on the bonds and increased the measured lifetime.

These two sets of experiments showed different failure modes and illustrated how different powering strategies, and possibly electrical setup, can influence failure mode. The first set of measurements at a constant cycle time, which most closely reflects operational use, verified that the Power Tester 1500A is able to detect immediately the appearance of degradation within the device's structure, including the die-attach and other compromised layers.

The second experiment clearly identified degradation of the bond wires because the forward voltage of the device was observed to increase stepwise, while with these powering options (current constant, constant heating power, and constant temperature rise), the thermal structure did not change for any of the samples tested. Of course, we have to be conservative in formulating conclusions because of the low number of samples. However, using the Power Tester 1500A, we can see that measurement results can differ depending on the cycling strategy, and lifetime predictions based on certain strategies can overestimate the real lifetime of power devices.

CONCLUSION

Reliability is a prime concern in many industries using high power electronics, and accelerated testing of these modules through a lifetime of cycles is a must for component suppliers, system suppliers, and OEMs. The MicReD Power Tester 1500A can power the modules through tens of thousands, potentially millions, of cycles while providing real-time failure-in-progress diagnosis.

As seen in the above examples, failure modes caused by die-attach degradation or bondwire damage can be easily and clearly identified using the Power Tester 1500A. This significantly reduces test and lab diagnosis time as well as eliminating the need for post-mortem or destructive failure analysis.

REFERENCES

1. Zoltan Sarkany, Andras Vass-Varnai, and Marta Rencz, "Investigation of Die-Attach Degradation Using Power Cycling Tests," *Proceedings of 15th IEEE Electronics Packaging Technology Conference*, pp. 780–784, Singapore, 2013.
2. Zoltan Sarkany, Andras Vass-Varnai, Sandor Laky, and Marta Rencz, "Thermal Transient Analysis of Semiconductor Device Degradation in Power Cycling Reliability Tests with Variable Control Strategies," *Proceedings of SEMI-THERM 30*, pp. 236–241, San Jose, CA, 2014.

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