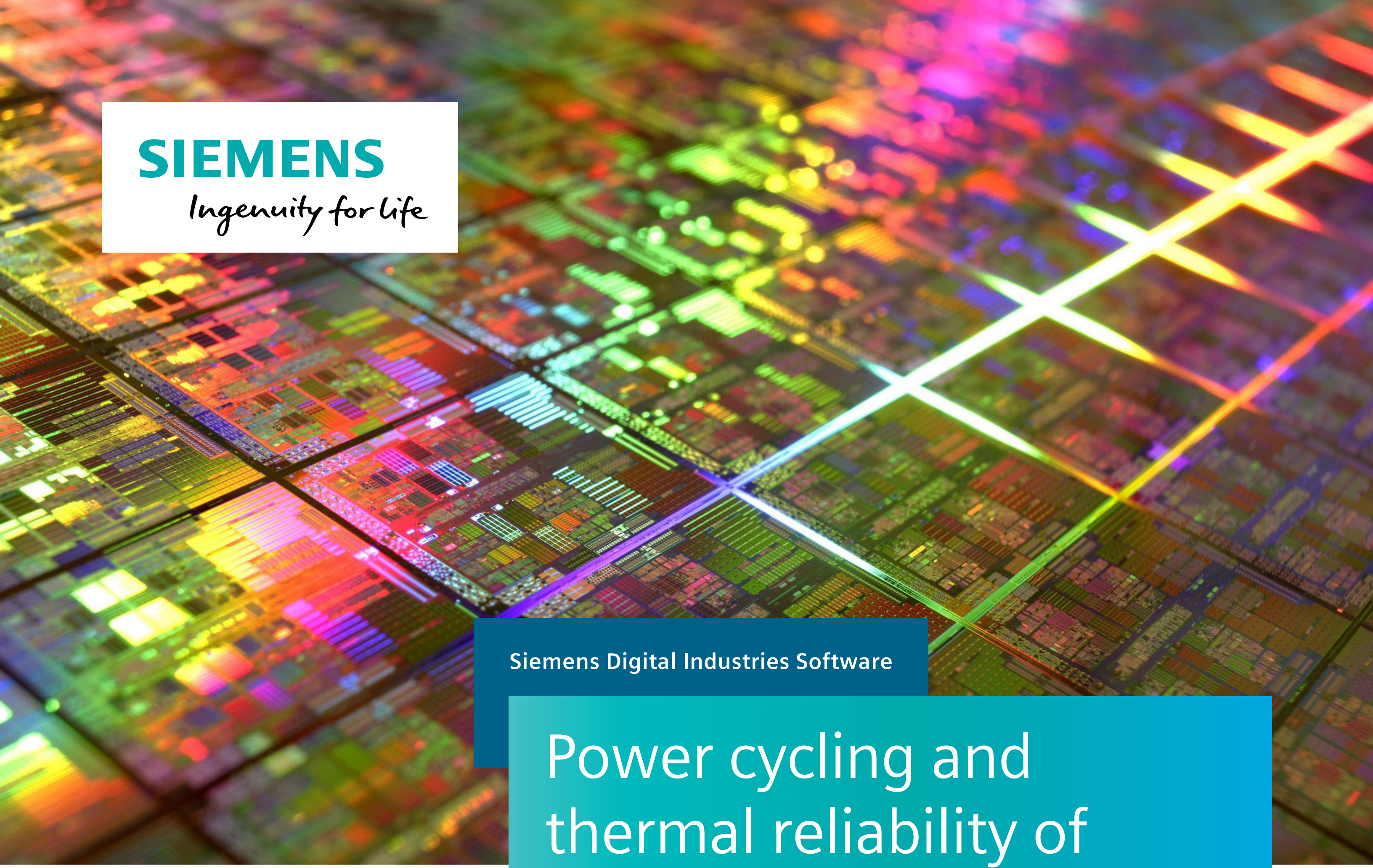

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Power cycling and thermal reliability of automotive IGBTs

Mechanical analysis

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Introduction

Introduction

The automotive industry is faced today with an increase in electrification of cars over the next 20 years due to market and environmental demands (figure 1). Initially hybrid electric vehicles (HEVs) such as the market-leading Toyota Prius have been driving this thrust but ultimately over the next 20 years full electric vehicles (EVs) should become the norm [1, 2]. However, automotive power electronics has to be designed with a 2-5 year lifetime in mind, corresponding to many thousands of hours of service and millions of power cycles. Such power electronic devices have to be able to withstand temperatures up to 200°C. Reliability is therefore especially critical to this power electronics application and cost of failure can be problematic. With the energy demands of industrial electronic systems increasing, automotive power electronics and component suppliers are faced with the challenge of providing highly reliable systems needed for automotive OEMs. High reliability of power electronics in particular is known to be directly linked to operating temperature.

Figure 2 illustrates typical power electronics components to be found inside an HEV today; IGBT power modules with associated liquid cooling, converters, inverters, HV batteries and motors.

By way of IGBT module examples, this white paper illustrates how this issue can be addressed.

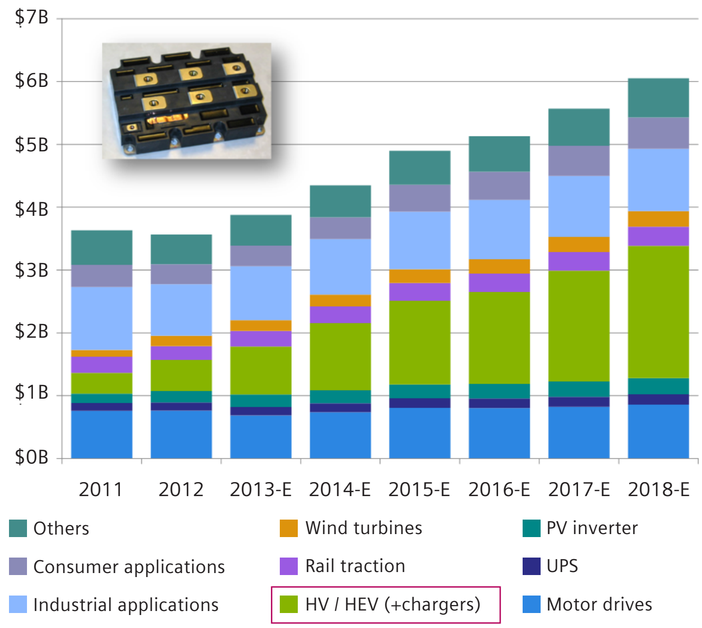

Figure 1: Predicted growth in IGBT markets and applications to 2018 [3].

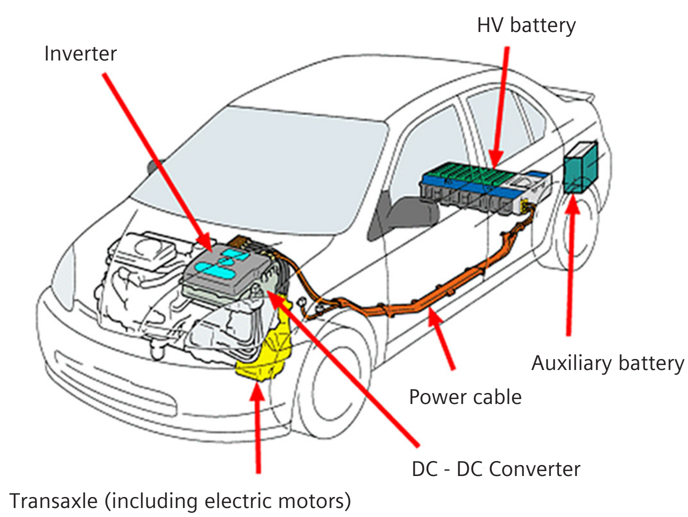

Figure 2: Power electronics components inside a HEV.

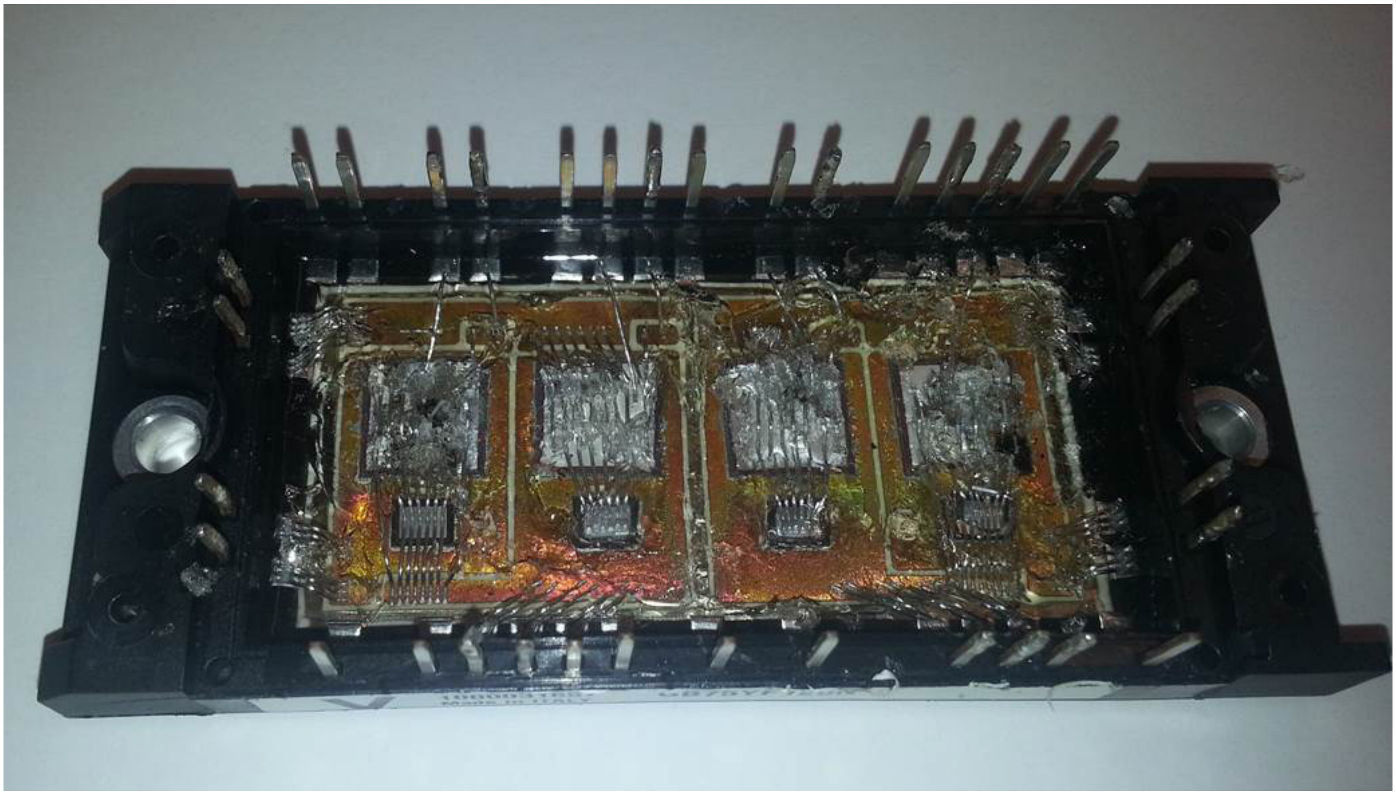

Figure 3: IGBT module after experiencing thermal damage.

The challenge of reliability under high loads and long lifetimes

Power electronics components such as MOSFETs, diodes, transistors, and IGBTs that are used wherever electrical energy is generated, converted, and controlled are seeing higher energy demands in both consumer and industrial applications. The challenge for manufacturers of power modules is to increase the maximum power level and current load capability, while maintaining high quality and reliability. With increasing energy load pressures, power electronics innovation has resulted in new technologies such as direct bond copper 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. These 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. All have in effect contributed to the thermal path in the device being improved. However, thermal and thermal-mechanical stress on these systems can still cause failures related to power cycling and heat effects. These stresses can lead to problems such as bond wire degradation (figure 3), die attach fatigue, delamination of stack-ups, and die or substrate cracks.

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.

Using a power tester to accelerate testing and diagnosis

A possible solution to expensive traditional “post-mortem” failure analysis of power electronics is the Simcenter POWERTESTER™ 1500A. It is the only machine available today built for manufacturing as well as laboratory environments that do automated power cycling while producing analytical thermal data for real-time failure-in-progress diagnosis (figure 4). It can perform lifetime testing to test the reliability of applications that use power electronic modules.

The Simcenter POWERTESTER 1500A is a robust industrial implementation of the tried–and-proven highly accurate Simcenter T3STER™ thermal measurement and characterization technology [4] that enhances capabilities of electronic components, LEDs, and PCB systems as well as high power electronics. The Simcenter POWERTESTER 1500A is unique in that it provides fully automated thermal 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 5).

For analyzing MOSFET, IGBT, and generic two-pole devices, the Simcenter POWERTESTER 1500A senses current, voltage, and die temperature while it uses “structure functions” [5] to record changes or failures in the package structure over time. The machine can be used to enhance and speed up power electronic package development, reliability testing and batch checking of incoming parts before production.

Figure 4: The Simcenter POWERTESTER 1500A is built for use in development and manufacturing environments.

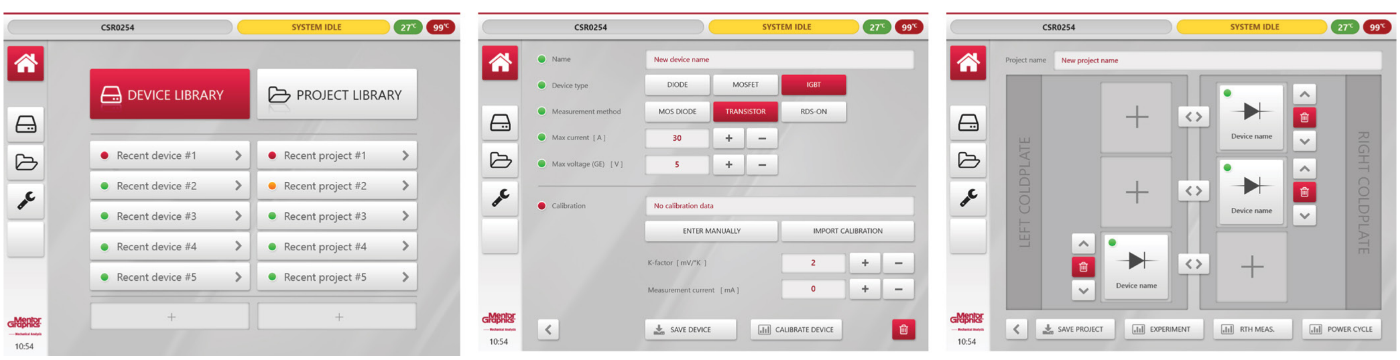

Figure 5: The Simcenter POWERTESTER 1500A touch-screen interface (left to right): main screen, device creation, and placing devices on the cold plate.

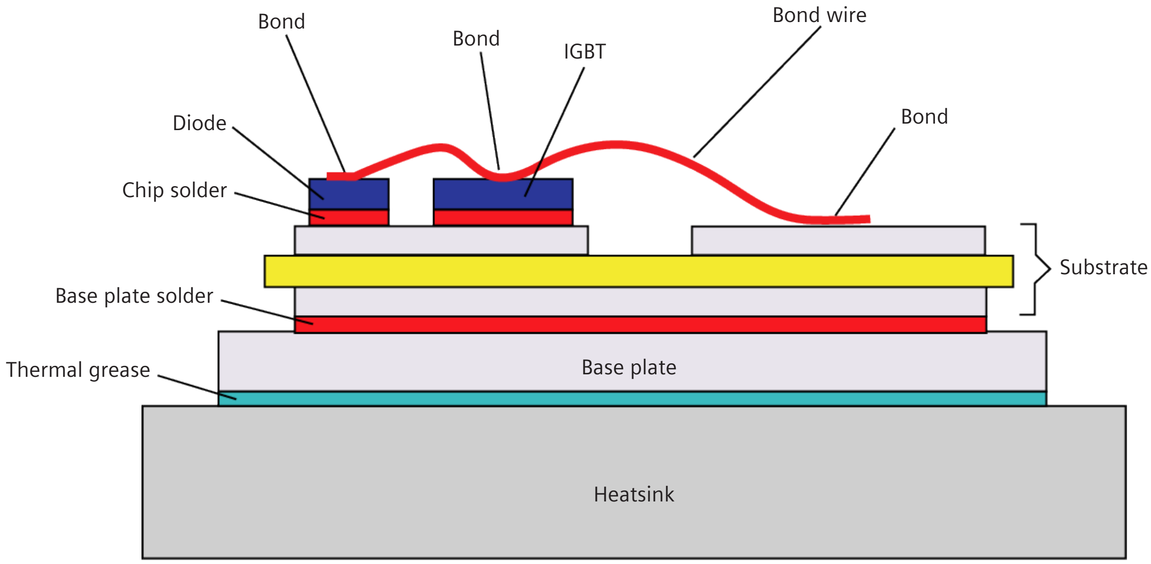

Figure 6: Cross-section of a typical IGBT module.

While running power cycles, real-time structure function analysis shows the power electronics 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 should not be as 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 defined at the start.

With the Simcenter POWERTESTER 1500A, power electronics suppliers are 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 power electronic package products with high requirements for reliability over the long-term will be able to test at the system level.

The Simcenter POWERTESTER 1500A is designed to follow the JEDEC Standard JESD-51-1 static test method [5]. 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 changes in partial thermal resistances in the heat conduction path. The Simcenter POWERTESTER 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 experiencing power cycling, it does regular measurement of R_{th} during the cycling, monitors system parameters such as voltage and current, and automatically increases R_{th} measurement frequency as required.

Testing and characterization data produced by the Simcenter POWERTESTER 1500A can also be used to calibrate and validate detailed computational fluid dynamics (CFD) models in Simcenter Flotherm™ software and Simcenter FLOEFD™ thermal simulation software [6] for even more accurate fluid flow and thermal simulation.

Real-time 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 6). 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.

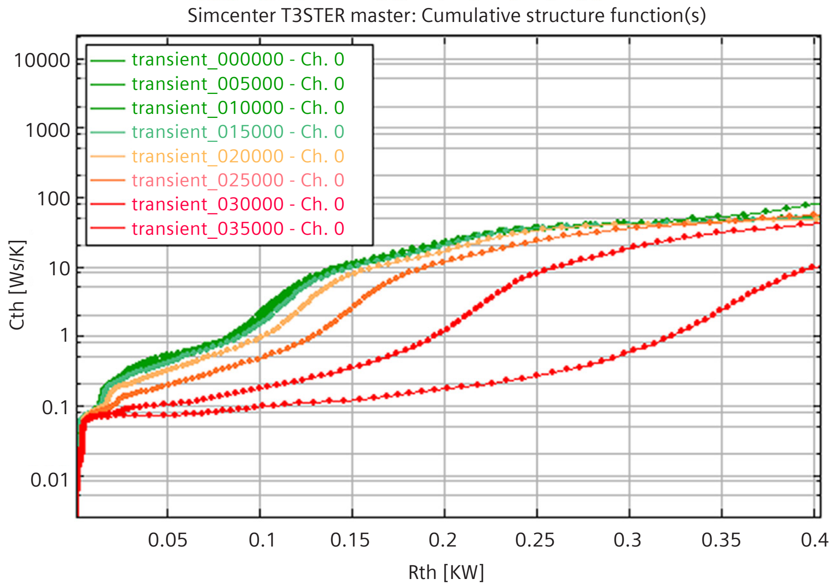

Figure 7: Structure functions of sample 0 corresponding to control measurements at various time points.

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 coefficients of thermal expansion, which can cause degradation or complete failure.

We conducted two 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 [7, 8].

The modules were fixed to the liquid-cooled cold plate integrated into the Simcenter POWERTESTER 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 Simcenter POWERTESTER 1500A.

The gates of the devices were connected to their drains (the so-called MOS 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.

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 under test, 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 7 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 burnt spots could be seen on the chip surface.

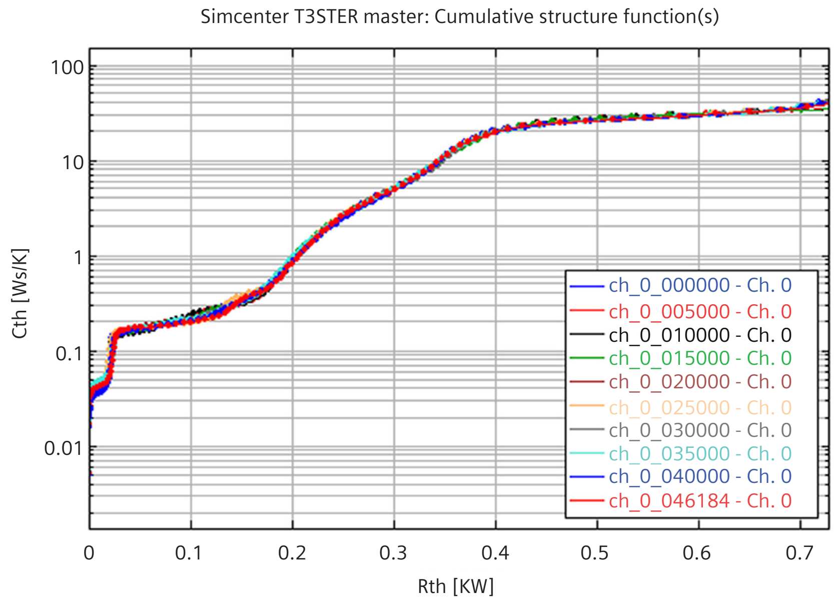

Figure 8: Change of the structure function of IGBT1 during the power cycling.

A second set of tests were performed on an identical set of samples using the different powering strategies supported by the Simcenter POWERTESTER 1500A. The two half-bridges in the module were mounted on the same baseplate but on separate 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 Simcenter POWERTESTER 1500A:

1. Device voltage with heating current turned on
2. Heating current applied in the last cycle
3. Power step
4. Device voltage after heating current turned off
5. Device voltage before heating current turned on
6. Highest junction temperature during the last power cycle
7. Lowest junction temperature during the last power cycle
8. Temperature swing in the last cycle
9. 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 8).

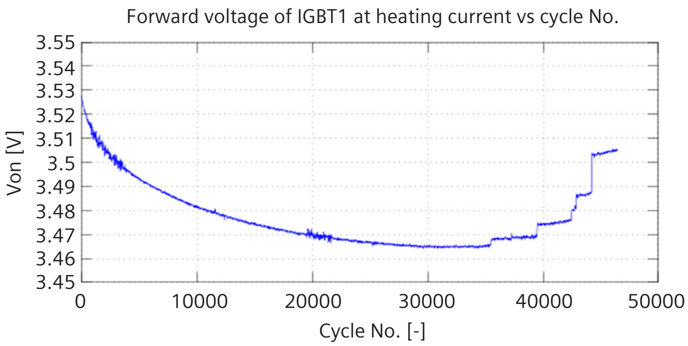

Figure 9: Forward voltage of IGBT1 at heating current level as a function of applied power cycles.

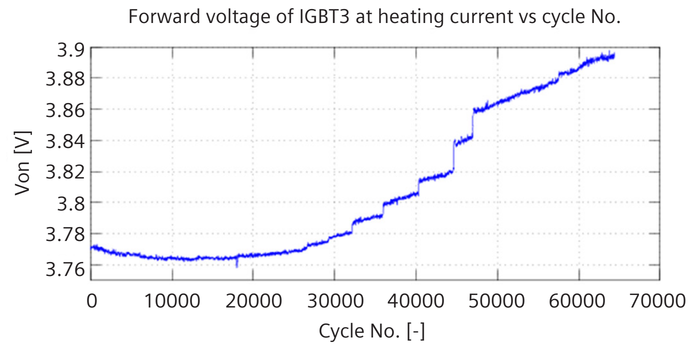

Figure 10: Forward voltage of IGBT3 at heating current level as function of applied power cycles.

We examined the evolution of device voltage during the experiment. Figure 9 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 10 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 Simcenter POWERTESTER 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. Larger sample sizes would provide more statistical data over time. However, using the Simcenter POWERTESTER 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 the automotive electric vehicle and hybrid electric vehicle industry which relies on high power electronics, and accelerated testing of power electronics modules through a lifetime of cycles is a must for component suppliers, system suppliers, and OEMs. The Simcenter POWERTESTER 1500A can power IGBT modules through tens of thousands up to 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 Simcenter POWERTESTER 1500A. This can dramatically reduce test and lab diagnosis time as well as eliminating the need for post-mortem or destructive failure analysis.

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