Thermal Management Details and their Influence on the Aging of Power Semiconductors

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<<Robustness>>,<<Power Semiconductor Device>>, <<Thermal Design>>, <<Reliability>>

Abstract

The major factor defining the wear and tear in power electronic components is temperature swing. The paper presents an insight to failure mechanisms and the benefits that can be gained if a holistic approach considering devices, adequate design-in and advanced thermal management is considered.

Introduction

The German *Energiewende* is among the projects predestined to hint out, what is expected of power electronic components today and what the challenges are, semiconductor manufacturers have to cope with. Renewable energy generation, lead by windmills and solar arrays, shall replace common centralized power plants within the next decades. Plants driven by fossil fuels like coal or gas are well known for their reliability and availability. Changing the German supply to renewable energies will have to achieve at least the same reliability and availability, leading to corresponding demands for the power electronic components involved. Windmills today are designed for a service life of 25 years, representing 50.000 operating hours at full power. This resembles almost 10 times the lifetime of a typical car. The demand in solar applications is similar and upcoming applications like energy storing systems (ESS) will be evenly challenging.

Failure Modes

Though power electronic components have no moving parts, they suffer from mechanical wear, driven by temperature swing. The internal stack of components as depicted in Figure 1 features materials with different coefficients of thermal expansion (CTE).

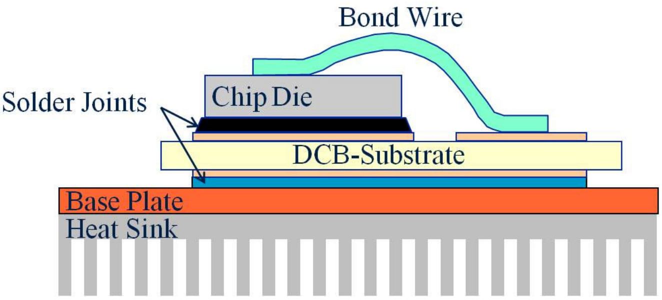
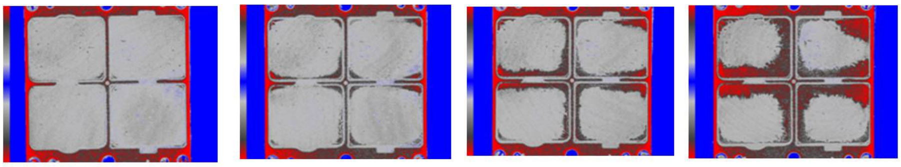


Figure 1: Stack of a power semiconductor, schematic overview

When the temperature of the complete stack increases, mechanical stress in the solder joints occurs as a consequence of the CTE-mismatch. This failure mode is referred to as thermal cycling. If the number of cycles in combination with the temperature level is sufficient, degradation of the solder joint between DCB and Base plate can be observed. The sequence seen in Figure 2 gives an insight on this effect for a power module with copper base plate.



200 Cycles **1000 Cycles** **2000 Cycles** **4000 Cycles**

Figure 2: Scanning Acoustic Microscopy (SAM) images of the IHM-A System Solder Joint during thermal cycling test. $\Delta T = 80K$, $T_{max} = 105^{o}$C, $t_{cycle} \approx 300s$

Delaminating of the solder joint reduces the area available for thermal transfer, thus increasing the thermal resistance. The module has reached end of life conditions when the thermal resistance junction to case R_{thjc} has increased by 20%. In case only short bursts of power are applied, the major temperature development takes place within the bond wires. This temperature swing leads to a change in the wires length. With both ends of the wire mechanically fixed, micro-movements occur that lead to stress at the bond wires connection interface and ultimately to a bond wire lift-off. The photo displayed in Figure 3 is a macroscopic view to such a failure. The failure mechanism is called power cycling.

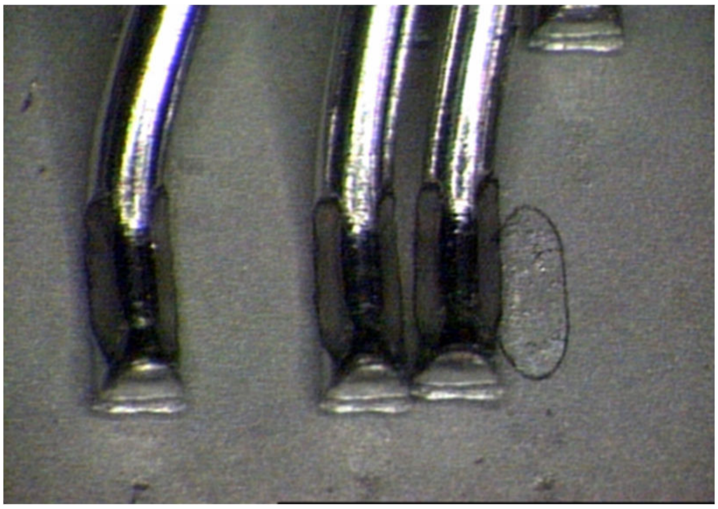


Figure 3: Bond wire Lift-Off due to power cycling

1 Design to Last

During development of any power electronic equipment, the combination of power semiconductor, heat sink and load profile can be considered a unit that will lead to a prediction of the temperature swing at the chip's junction. Usually, semiconductor manufacturers provide information that allows the designer to estimate a number of cycles that a power semiconductor will survive, based on the temperature swing predicted [1]. Knowing the number of cycles an application runs per day, a service life time can be estimated. The trade-off to be done is that financial aspects as well have to be considered as a conservative design may not be competitive. Throughout the last years, the rated current of power semiconductors has grown, leading to higher power densities within the power module. Though the reduction of the semiconductors volume does not reduce the inverter size by the same factor, it is a driving force towards smaller, cost-optimized designs.

As the chips current density $[A/cm^2]$ grew faster than their efficiency, the power density for the losses $[W/cm^2]$ also grew noteworthy, thus leading to a continuous increase in the chip temperatures. The opportunity arising for the designer from this development is a trade-off between increasing the lifetime or the output power, maybe both to a certain extend.

Figure 4 gives an insight to historical development of a 1200V/15A power module containing a three phase input rectifier, brake chopper and B6 output inverter (PIM). Within less than 20 years, the volume of the power device was reduced by more than 70%, the weight changed from 180g down to 24g.

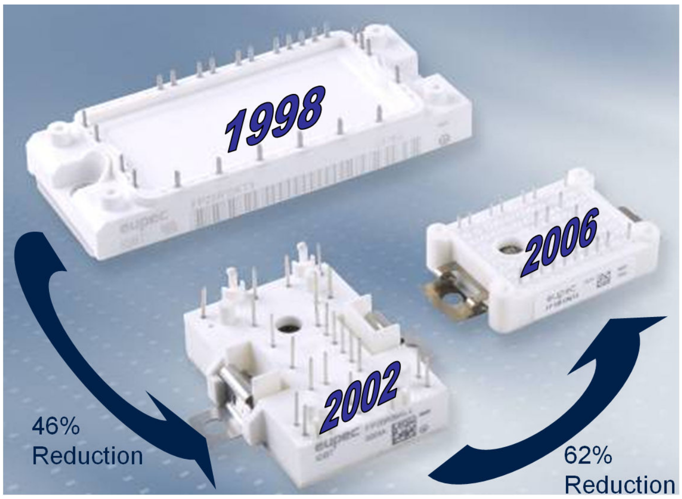


Figure 4: Development of a 15A PIM 1998-2006

Considering the thermal budget available within the design allows for several possible options:

1. Keep the new chip generation at the same temperature levels as before, leading to extended lifetime of a given design or
2. Keeping the output power at the same level but reduce the heat sink in volume will allow material reduction at higher temperature levels, achieving the same lifetime
3. Increase the output power using the existing heat sink, still at the same lifetime

Technologically, todays power devices have reached the limits of what is physically feasible and upcoming new technologies need to be implemented to cope with the increasing demands in future.

2 New Interconnection Technologies

Recently, new interconnection technologies to be used in power semiconductors have been introduced [2] hinting out that in future, silicon dies can be connected to DCBs without the need of soft soldering. Furthermore, copper wire bonding is introduced to cope with higher current density demands. The technology is completed by a high-reliability system solder joint [3] to achieve 10 times the lifetime of current devices. Parts of this new approach are already implemented in newly designed modules with a massive influence on the lifetime.
The Scanning Acoustics Microscope (SAM)-images given in Figure 5 clearly indicate the massive improvement of this new soldering. The picture summarizes a test that was terminated after 40.000 cycles were exceeded without reaching the end-of-life criterion given for this power module.

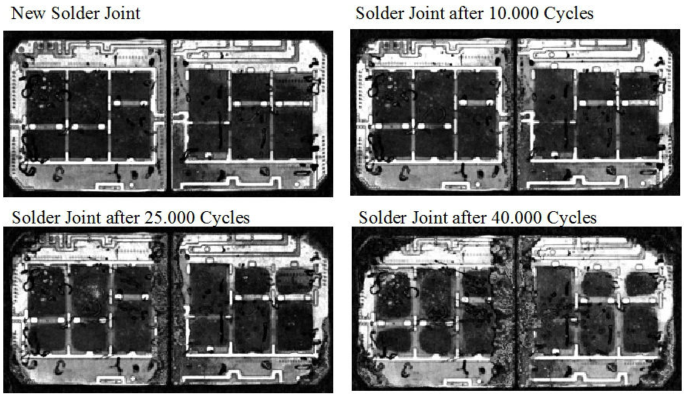


Figure 5: SAM-images of a system solder joint successfully passing a test exceeding 35.000 TC-cycles

A product manufactured according to todays processes is specified to survive 12000 cycles under these test conditions.

Besides the new soldering, copper bond wires as well have made it to series production in power modules. Just recently, modules featuring copper bonds to replace aluminum in system bonds, interconnecting DCBs were introduced as can be seen in Figure 6.

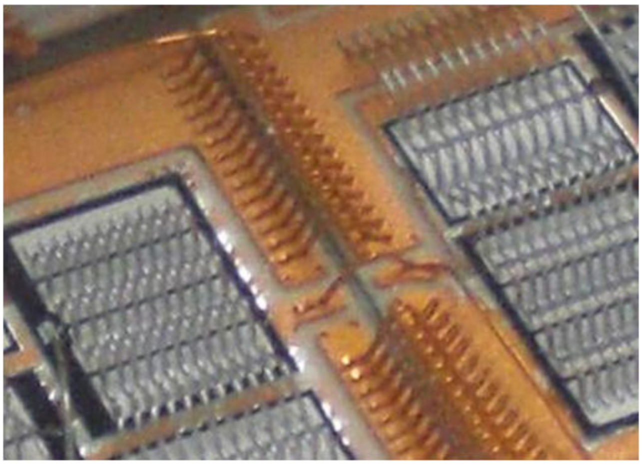


Figure 6: Copper wires connecting the DCBs of an Infineon FF600R12ME4

This too is considered a thermal management issue as the temperature of aluminum bond wires would have exceeded the thermal limits for the current targeted inside the power module.

Both technologies can be considered selective spin offs from Infineons .XT-Technology. This holistic approach will combine the next chip generation IGBT5 with a package featuring a new chip interconnection, copper wire bonding on copper chip surfaces and the newly developed high reliable soldering technique. A subsystem as used in a .XT-type module is given in Figure 7.

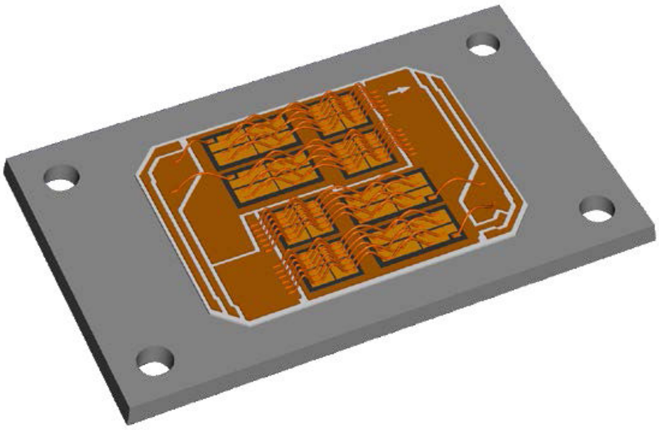


Figure 7: appearance of a DCB featuring the .XT-set of interconnections

3 Advances in Thermal Management

Though semiconductor manufacturers strive for improvements in constructing power modules, one important aspect remains with the assembly at the customers site. A thermal interface between the semiconductor and the heat sink has to be installed. This layer is needed to achieve a proper and long-term stable transfer of the heat, generated inside the module, to the heat sink. Evaluation of materials returned from the field for failure analysis has substantiated the assumption, that especially the long-term stability of common greases is overestimated [4, 5]. An application that was designed to operate for 10 years had suspiciously high failure rates after only 5 years.

Analysis on the power modules revealed thermal overload as a failure. However, measured data seemed to contradict this statement. Deeper analysis of the application included the investigation of the whole drive instead of a single power module. In doing so, the thermal interface material in use was examined as the appearance of the heat sink lead to the conclusion that a destruction of the thermal transfer path was at the bottom of the failure. In Figure 8, the heat sink investigated is displayed. It clearly shows traces of grease oozing out from below the power module. At some point, the thermal transfer path was destroyed leading to the thermal overload of the semiconductors.

Figure 8: Heat sink of a failed inverter with no thermal grease remaining below the power module's hot spot

A laboratory setup was build to verify that the failure was a consequence of failing thermal transfer. The identical power module was equipped with the grease used in the inverter and thermal cycling was done, while the temperature was measured using an IR-Camera.
As can be seen in Figure 9, the grease in use suffers from being pumped out from below the module.

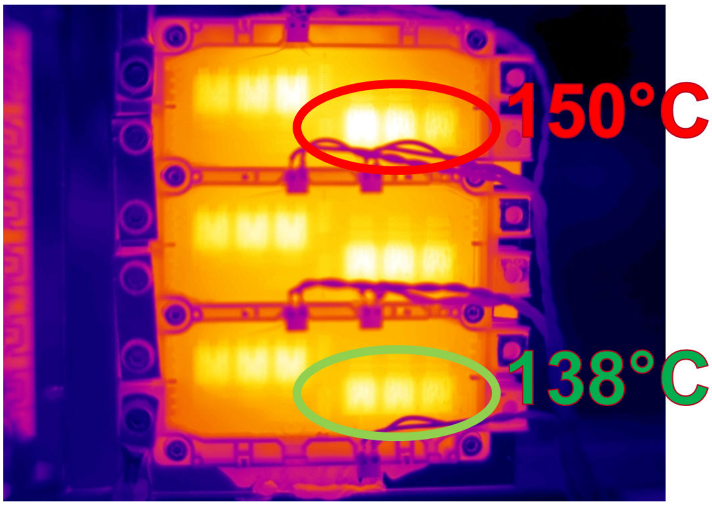


Figure 9: Laboratory test to stress the thermal grease in use. Grease oozing out rapidly leads to higher local chip temperature

As this is an often reoccurring effect, new thermal interface material has been developed to cope with the harsh demands in power electronics. The new solution [6] turns out to be superior in both, thermal transfer capabilities and long-term stability.
To carry the results from the lab to the real application, the new material was used in a stress test for a converter with 2MW of output power. Here too, the modules are mounted in vertical direction. The test's target is an operation for at least 1000 hours under high stress. The growth in chip temperature is expected as a consequence of the high stress. A temperature of 150^{o}C is considered end of life as this will exceed the power module's specification and lead to accelerated aging in turn.
The results gained from the test are summarized in Figure 10.
With a first grease, the test failed after less than 600 hours. A second candidate was tested, here too the 1000 hour target could not be met. With the only difference in the test being the grease, this clearly showed the influence of this component.

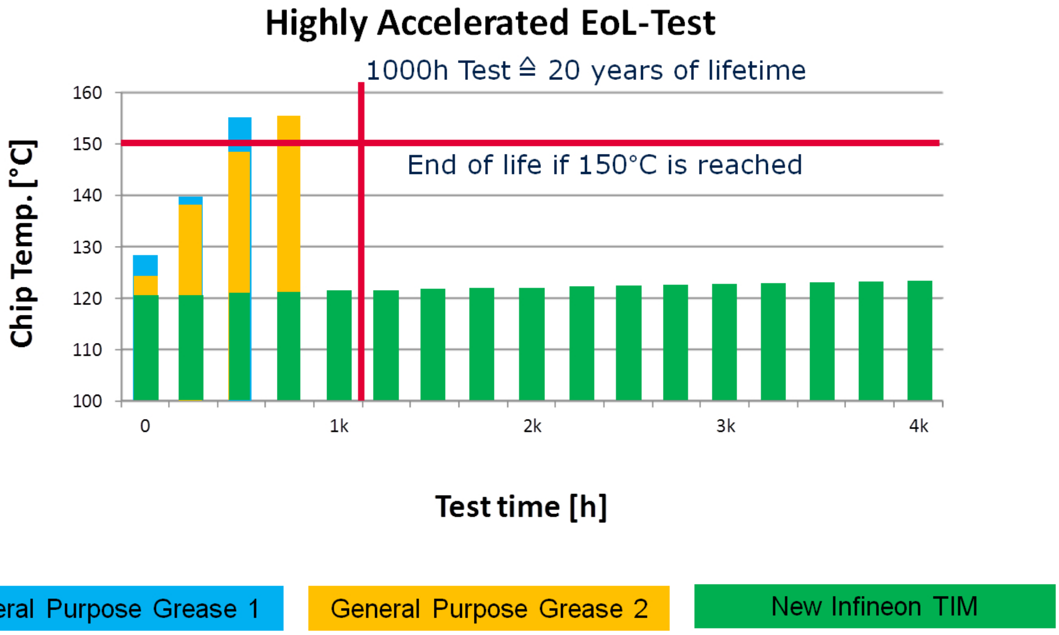


Figure 10: Different thermal grease solutions influencing a stress test to predict an inverter's lifetime.

A final test was started using the new TIM solution developed by Infineon. A first result was a reduction in chip temperature at the beginning of the test. This is a consequence of the improvement in thermal transfer. The test with this approach was discontinued after 4000 hours with no failure.
As the failure mechanisms are of exponential nature, these results hint towards a massive gain in lifetime for the inverter system under test.

4 Conclusion

The wear and tear in power semiconductors is a consequence of temperature swing during operation. The increasing demands are driven by the urge to increase the power density while reducing the resources in use, along with the costs for the design. Semiconductor manufacturers therefore continuously develop more robust devices. Though the designer greatly benefits from the improvements, care has to be taken to properly assemble those devices and build a reliable long-term stable interface. If those criteria can be met, an increase in lifetime for todays and also future generations of power devices can be expected.

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